Buffer Gas Cooling

A tool for trapping neutral atoms

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April 8, 2008

LBNL

EETD Seminar

Many Thanks

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Outline

Background

- Trapping and cooling
- Laser cooling: applications and limitations

Buffer gas cooling: Techniques and applications

- Advantages over laser cooling
- Basic physical principles
- Technical challenges and solutions
- Trapping $1\mu_B$: Li, Cu, Ag
- Future Experiments: Non-S state atoms and further cooling

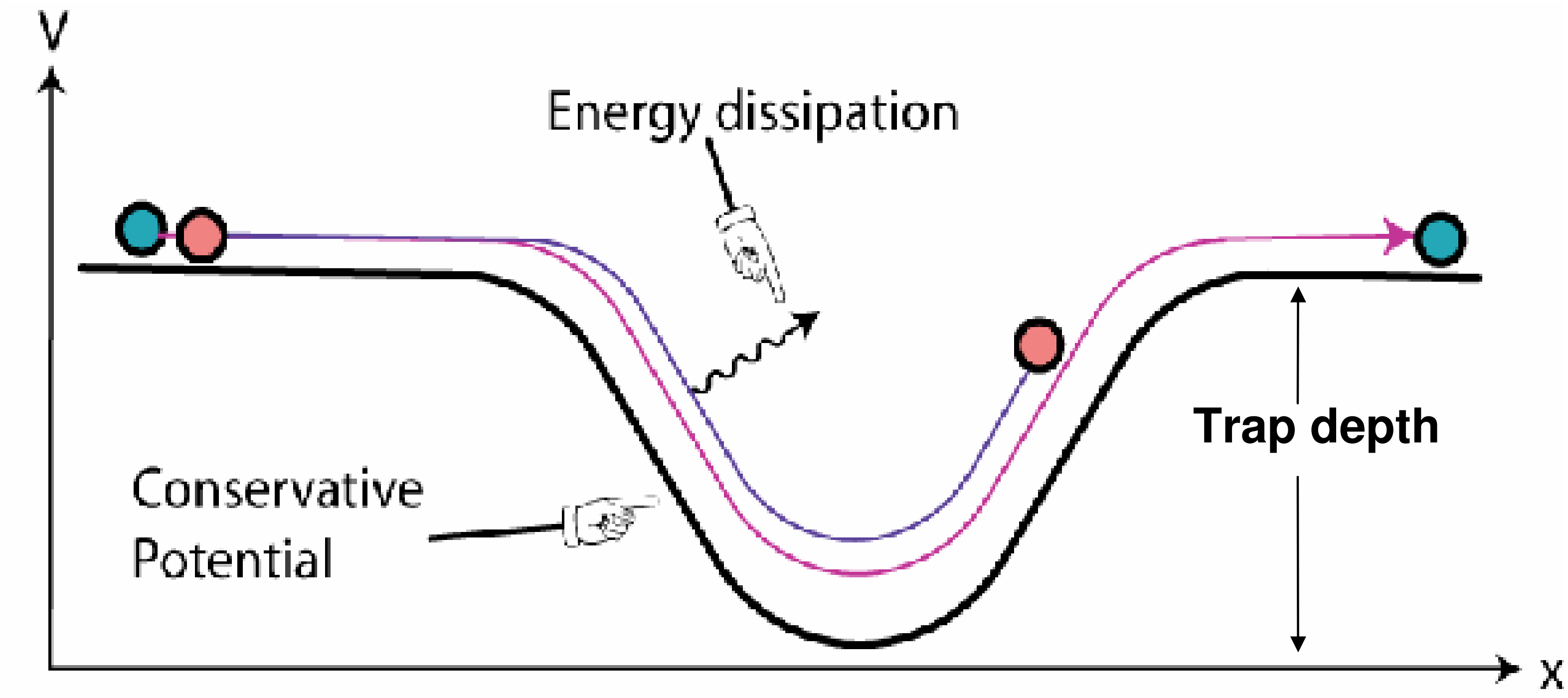
Why am I here today?

- Transition to sustainable energy science
- Activities of PV@MIT

Trapped Atom Science

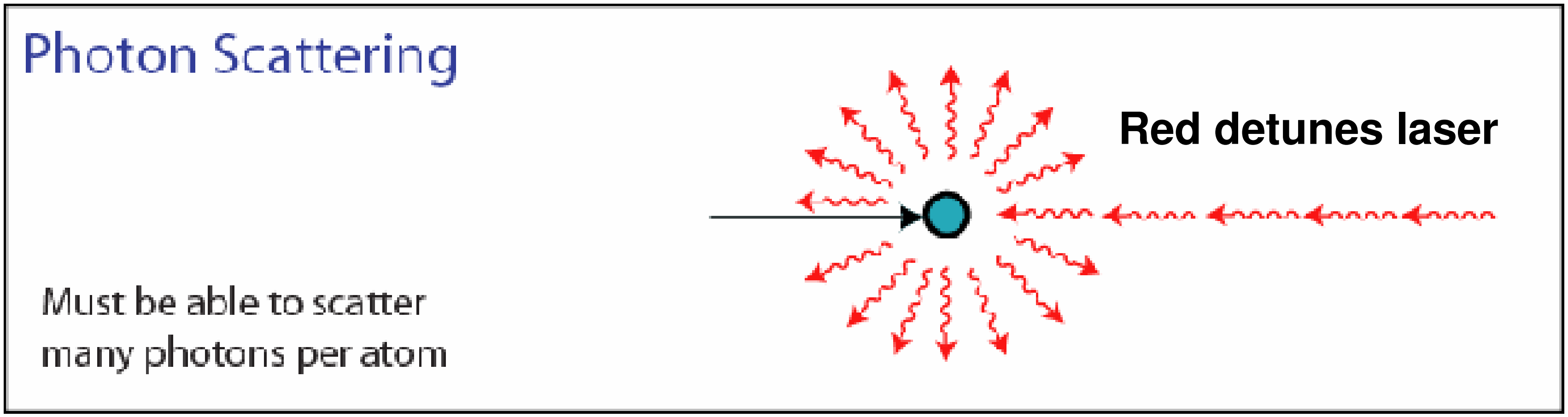
- Study quantum behavior near absolute zero temperature
- Precision measurement
  - Atomic clocks
- Quantum information
  - Manipulate quantum states for computing and secure communication
- Simulate solid state systems
  - High T_C superconductors

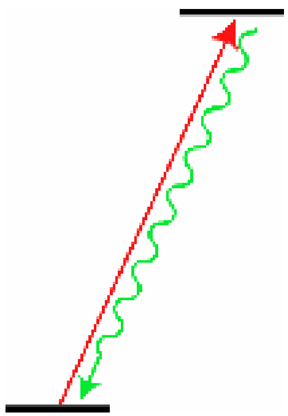
Trapping and Cooling



Trapping requires cooling!

Laser Cooling: A Common Approach

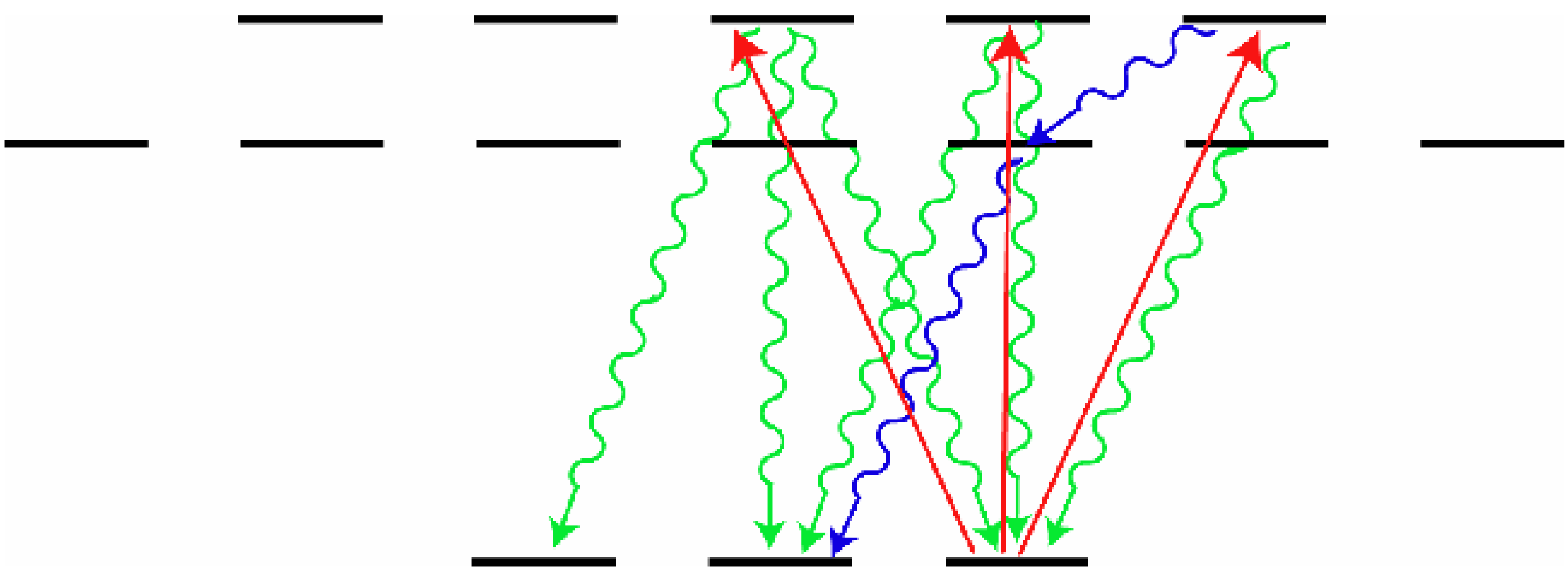




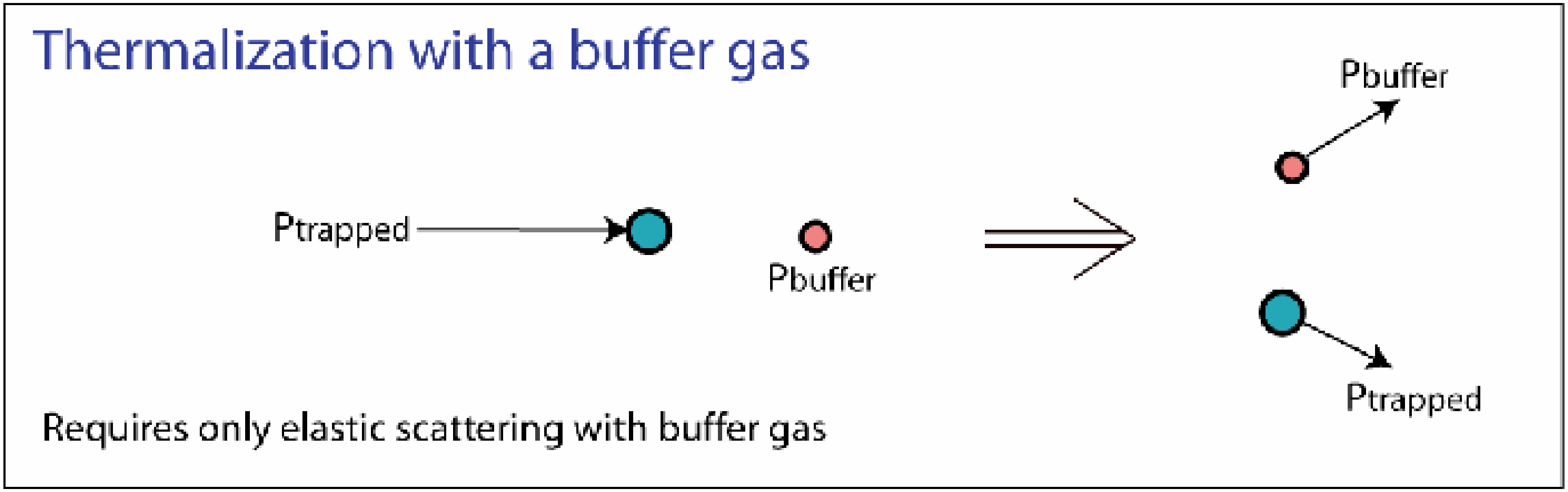
Ideally your atom is a two level system: After emission your atom is back where it started, waiting to be cooled further.

Laser Cooling Limitations

Complex structure makes laser cooling a challenge for most atomic species



Buffer Gas Cooling

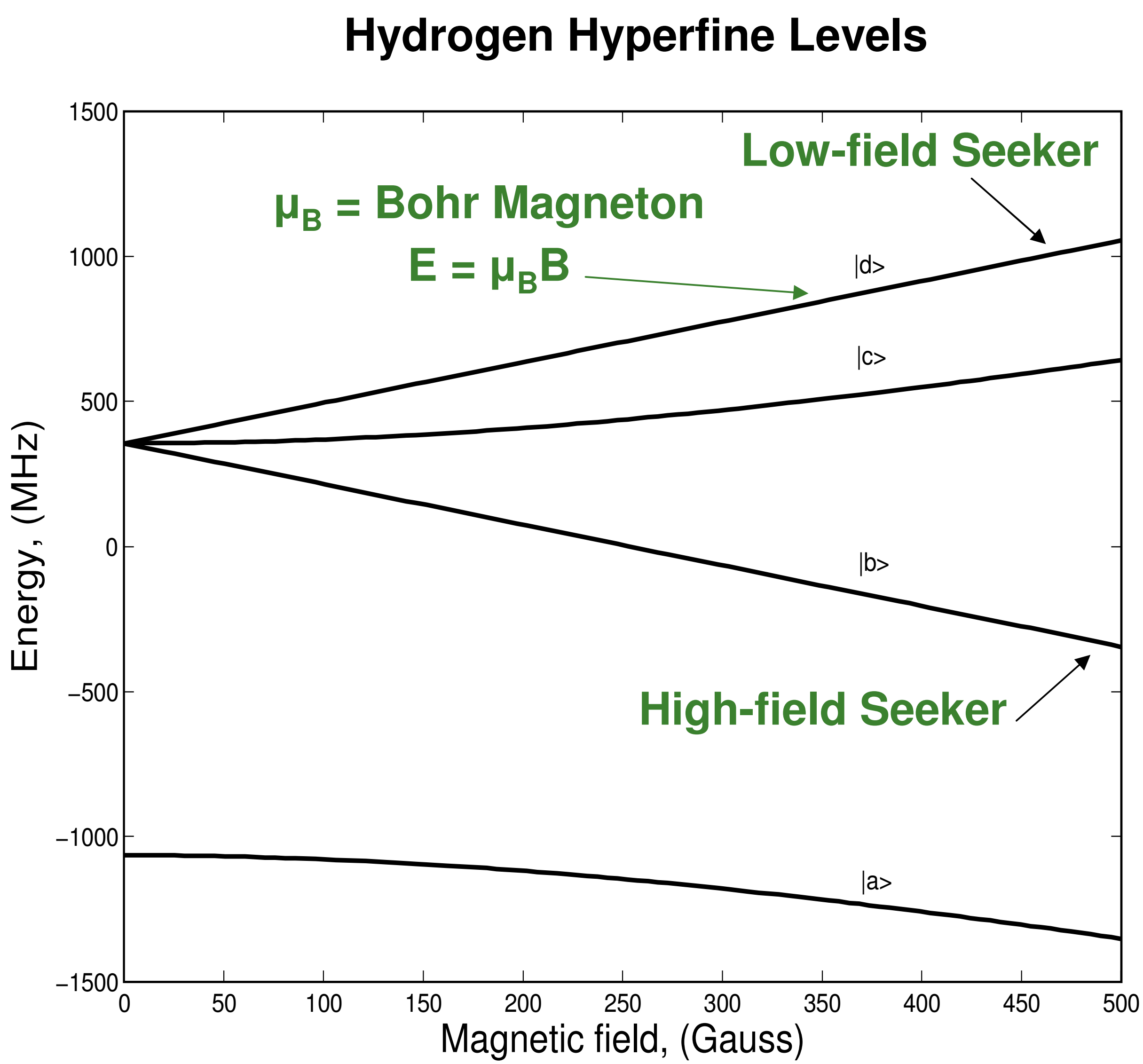


Not dependent on internal states.

You can cool all kinds of species (including molecules)!

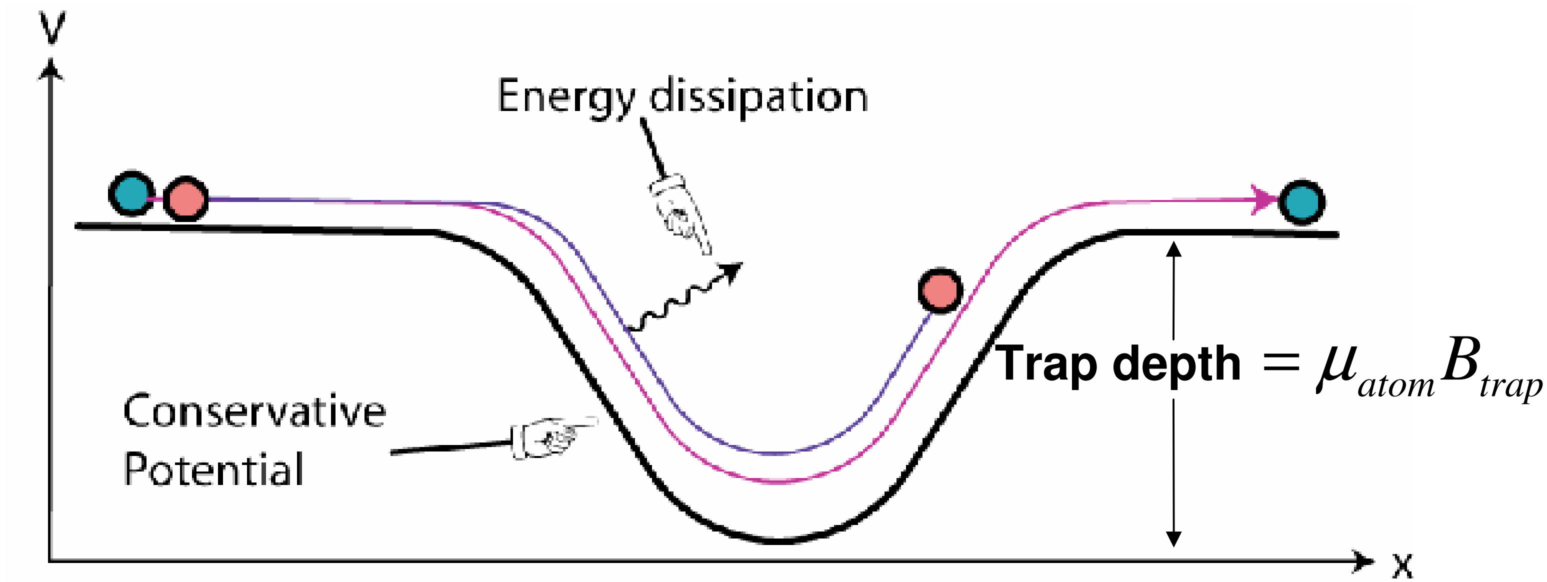
But can you trap everything?

Magnetic Trapping



Atom	~ μ_{atom} (μ_B)
H, Li, Na Cu, Ag, Au	1
^{4}He*	2
N, Bi, Pr	3
Ni	5
Cr, Fe, Co	6
Ho	9
Dy	10

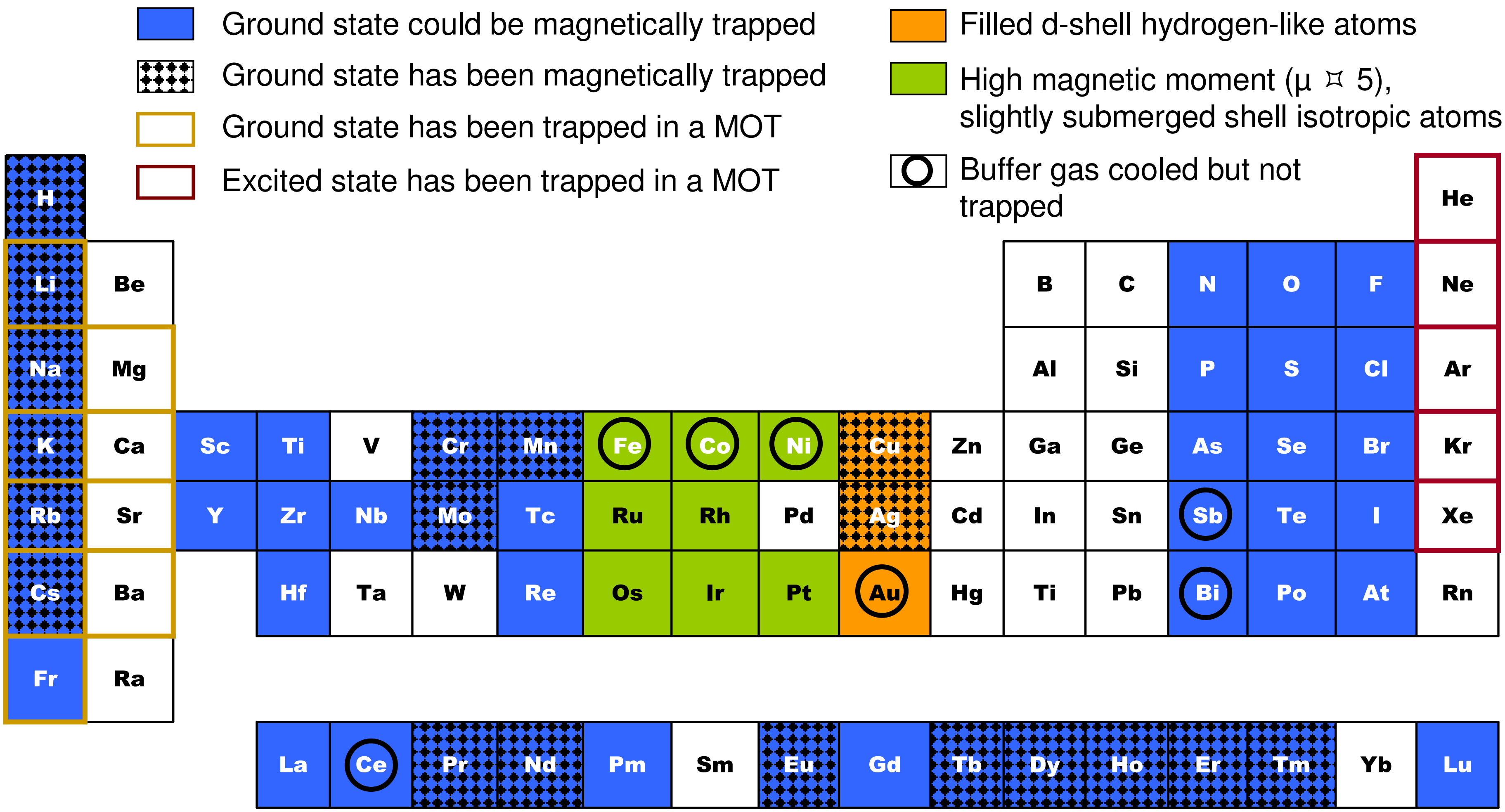
Magnetic Trapping



$$\eta = \frac{\mu_{atom} B_{trap}}{k_B T} > 1$$

$$\frac{\mu_B}{k_B} = 0.67 \frac{\mathrm{K}}{\mathrm{T}}$$

Atom Trapper's Periodic Table

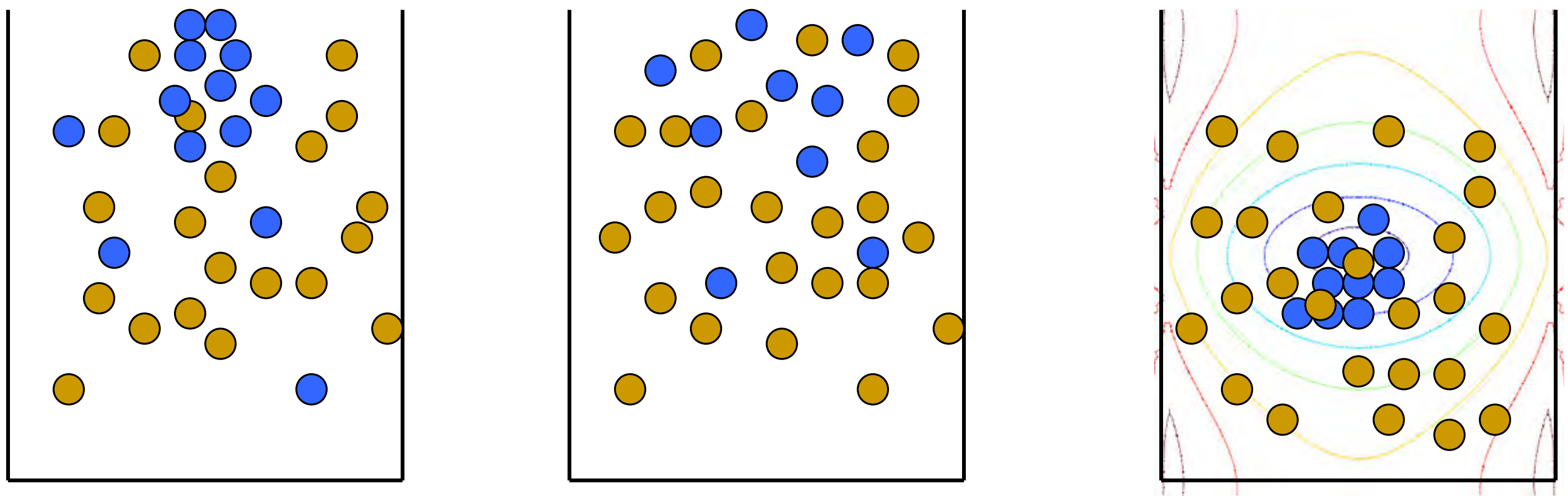


Basics of Buffer Gas Cooling

$T \approx 1000K$ $\qquad$ $T \approx 100\ mK$

^{3}He buffer gas

Paramagnetic Atoms



Thermalization ~ 100 collisions in 300μs

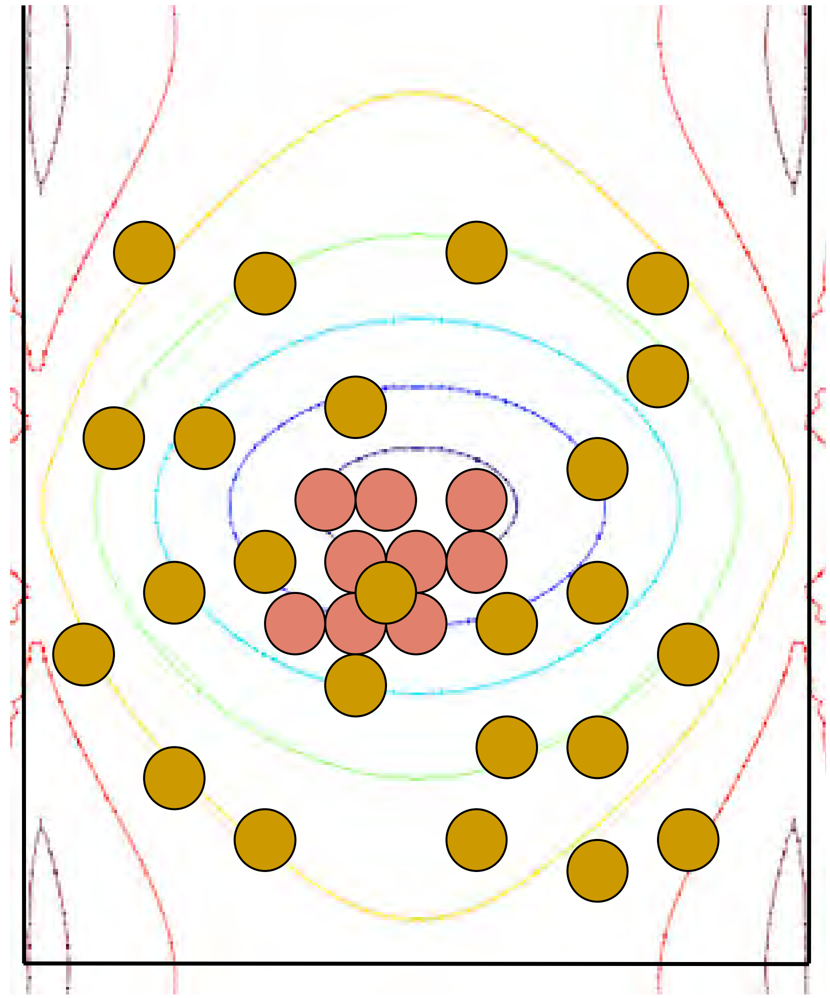
$n_{BG} = 10^{16}\ cm^{-3}$

Trapped Atoms!

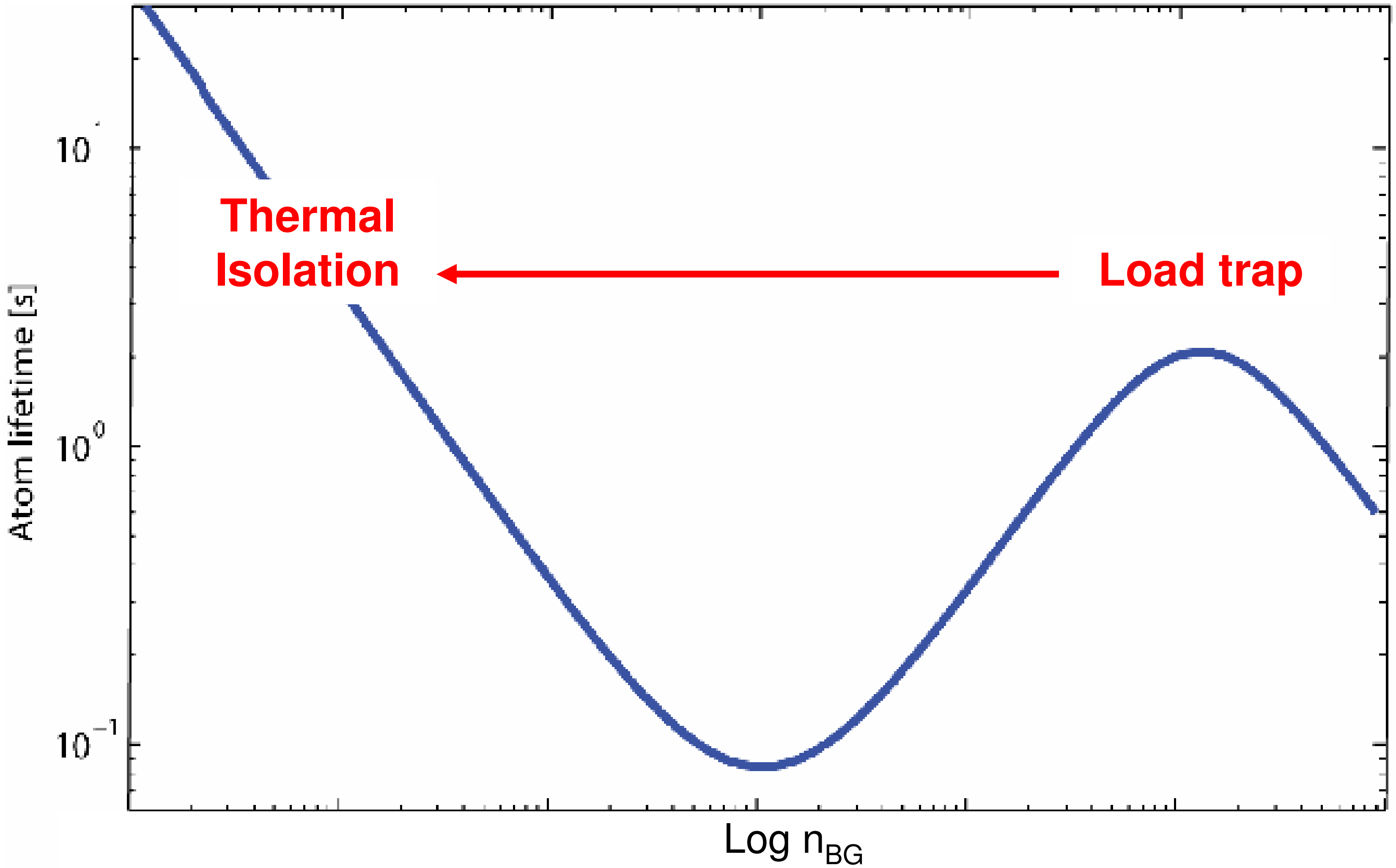
Limits of Buffer Gas Cooling

Although trapped…

- Thermally connected to walls by buffer gas
- Atoms can undergo collisions to put them in an untrapped state



BG Effects on Trap Lifetime



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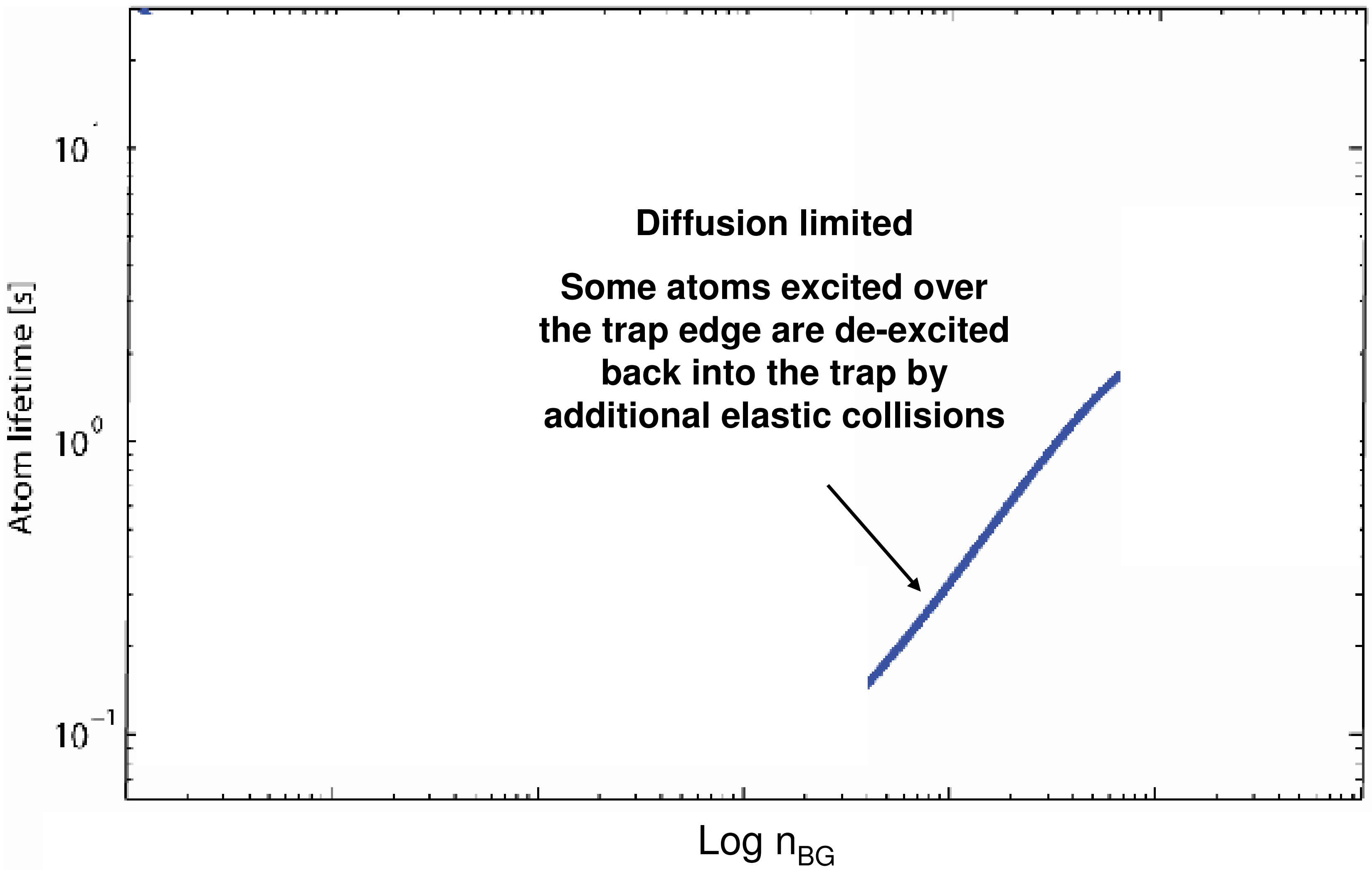

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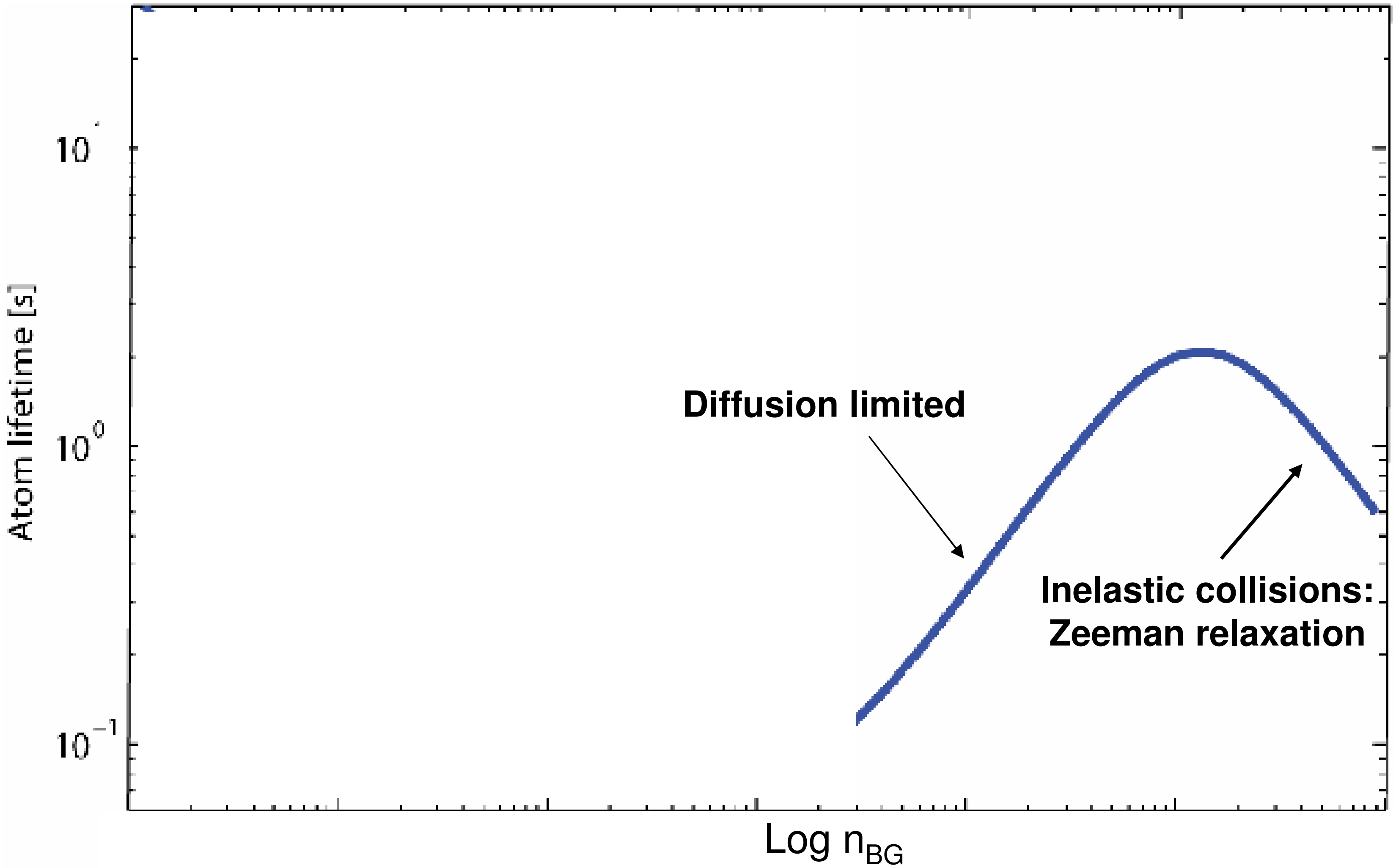
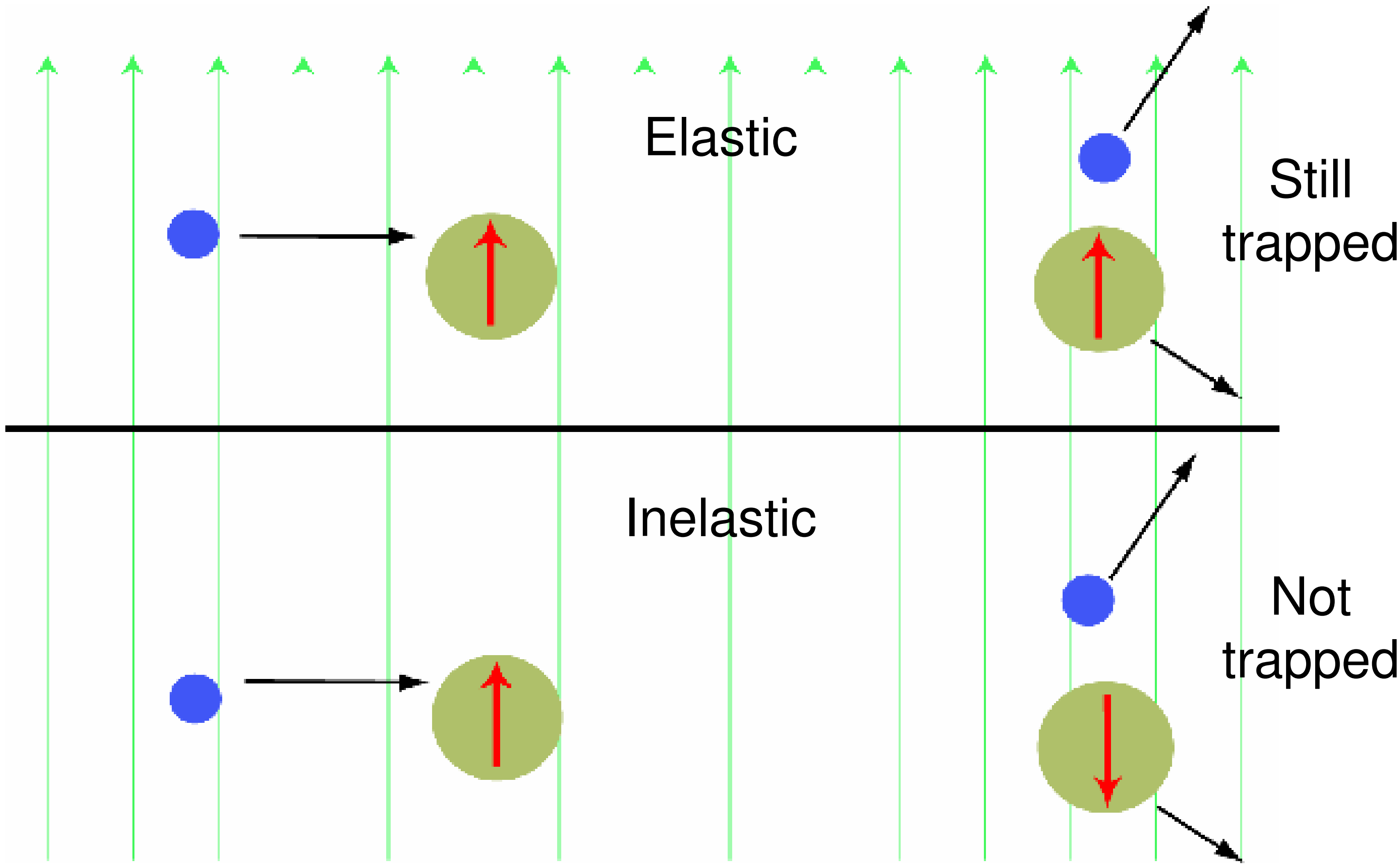
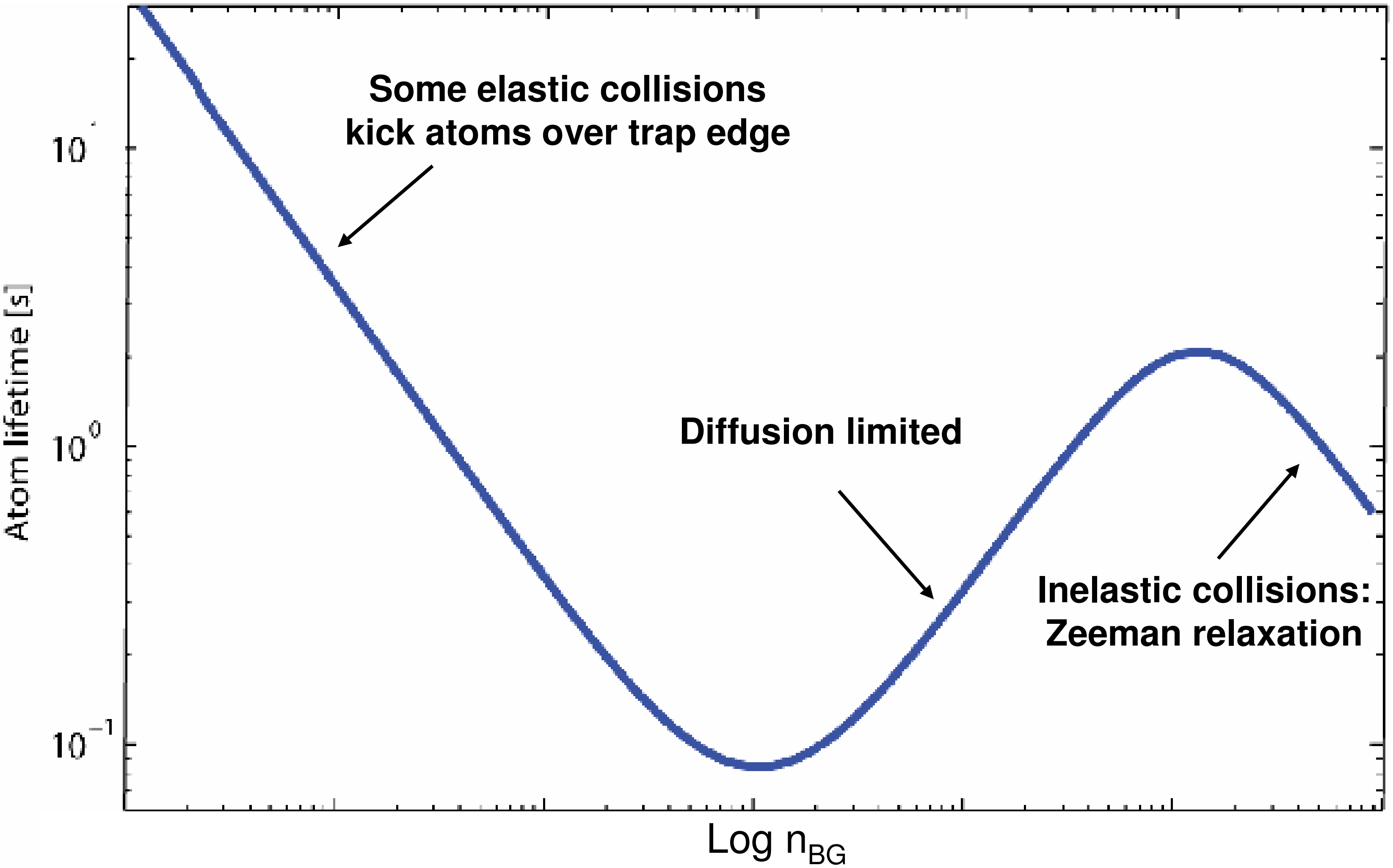


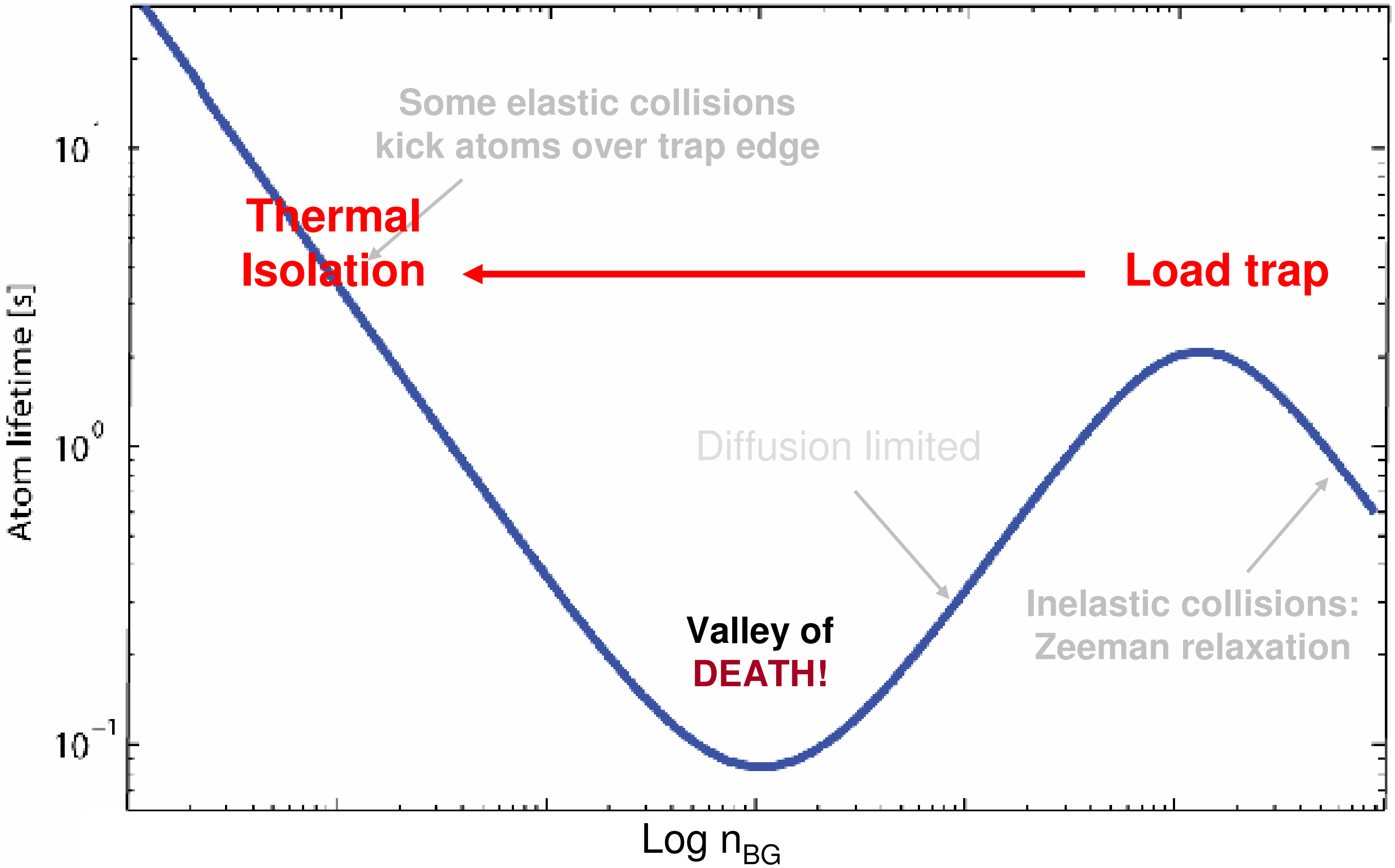
Elastic vs. Inelastic Collisions



BG Effects on Trap Lifetime



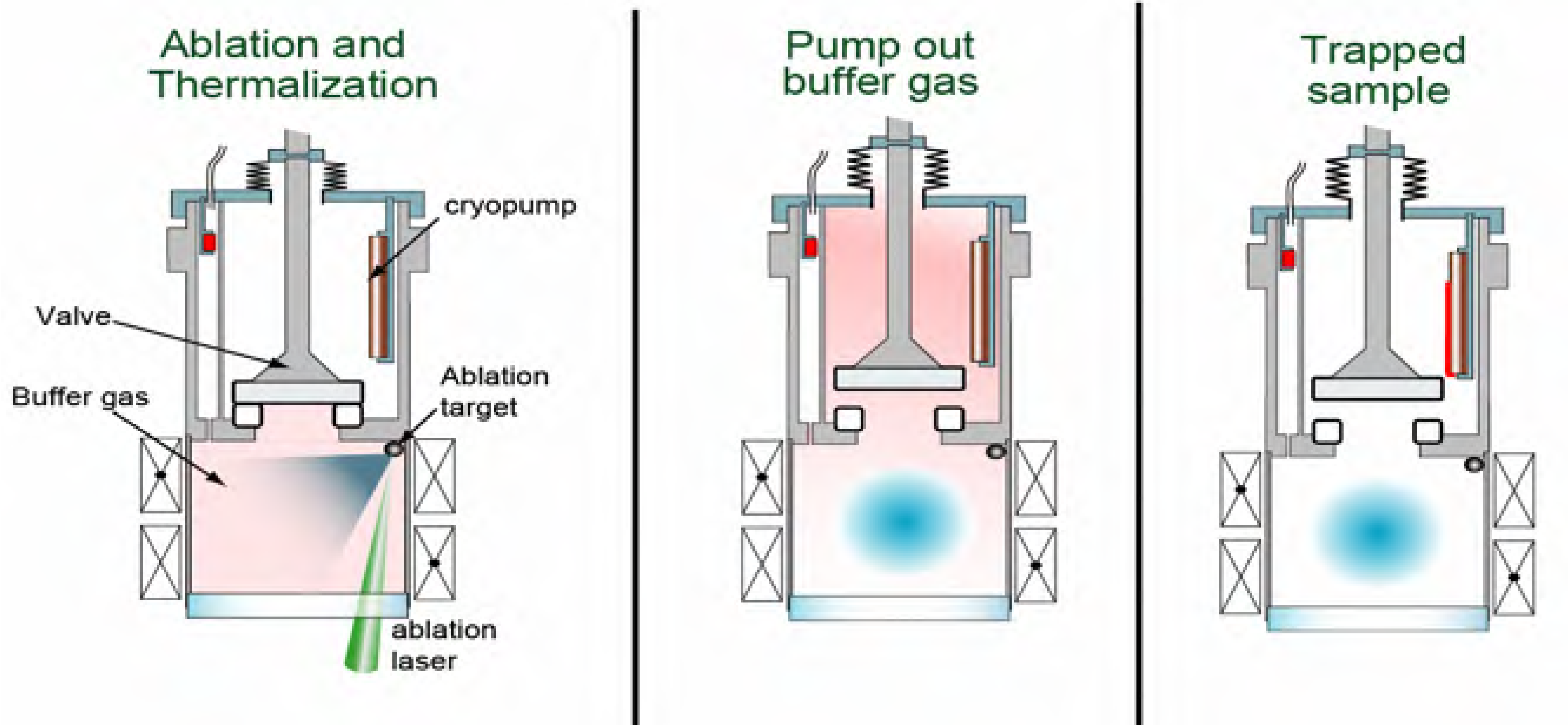
BG Effects on Trap Lifetime



Buffer Gas Cooling and Trapping Requirements

1. Cold non-magnetic buffer gas
   - ✓ He thermalized by dilution refrigerator (~100mK)
2. Atomic/Molecular source
   - ✓ Ablation, discharge, gas beam
3. Large magnetic field.
   - ✓ 4T superconducting magnet
   - ✓ 2.7K trap depth ↔ $\eta \sim 5\text{-}10$
4. Method to remove buffer gas
   - ✓ Fast cryogenic valve

Buffer Gas Loading Scheme



Ablate target ~1000 K

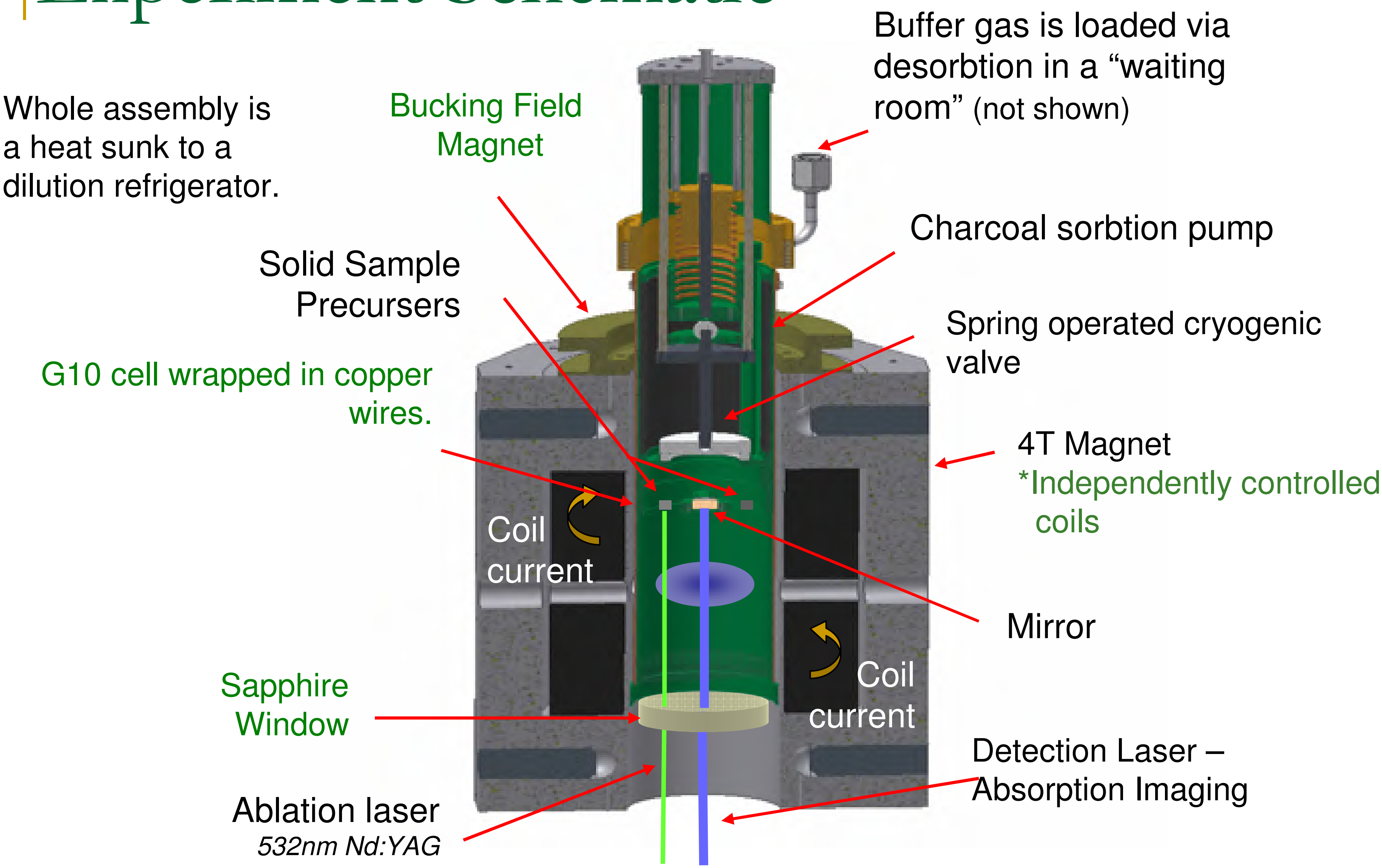
Thermalize and further cooling ~150K

Open valve to remove buffer gas

Study atoms

Further evaporative cooling

Experiment Schematic



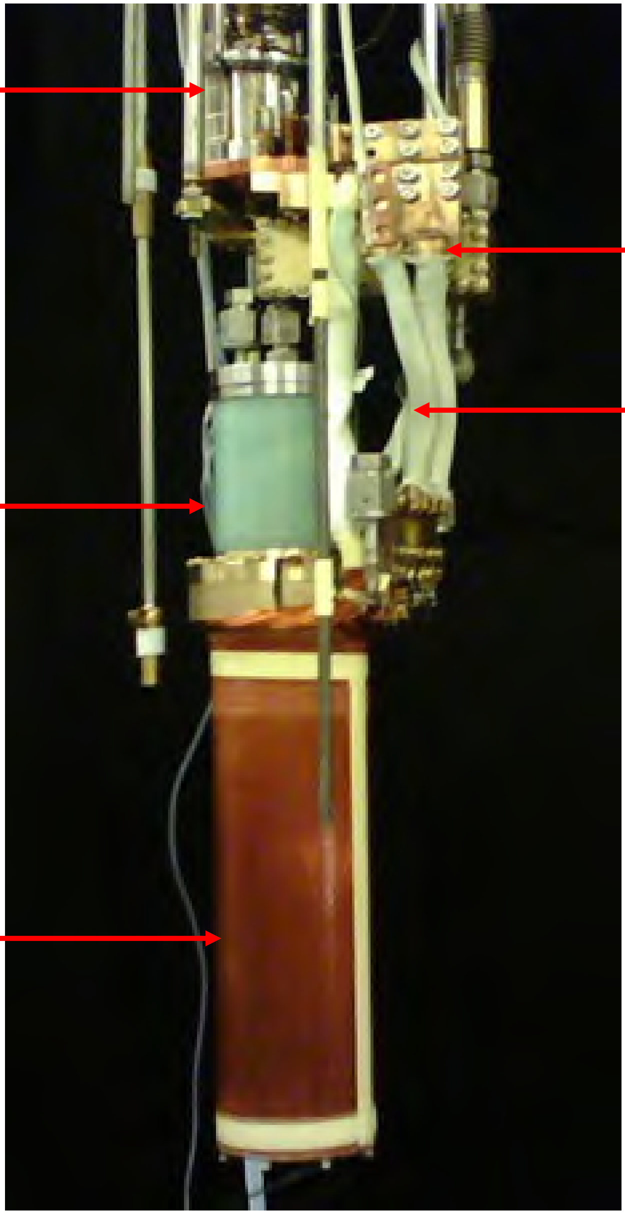
Dilution refrigerator mixing chamber

Pulley box for pull line

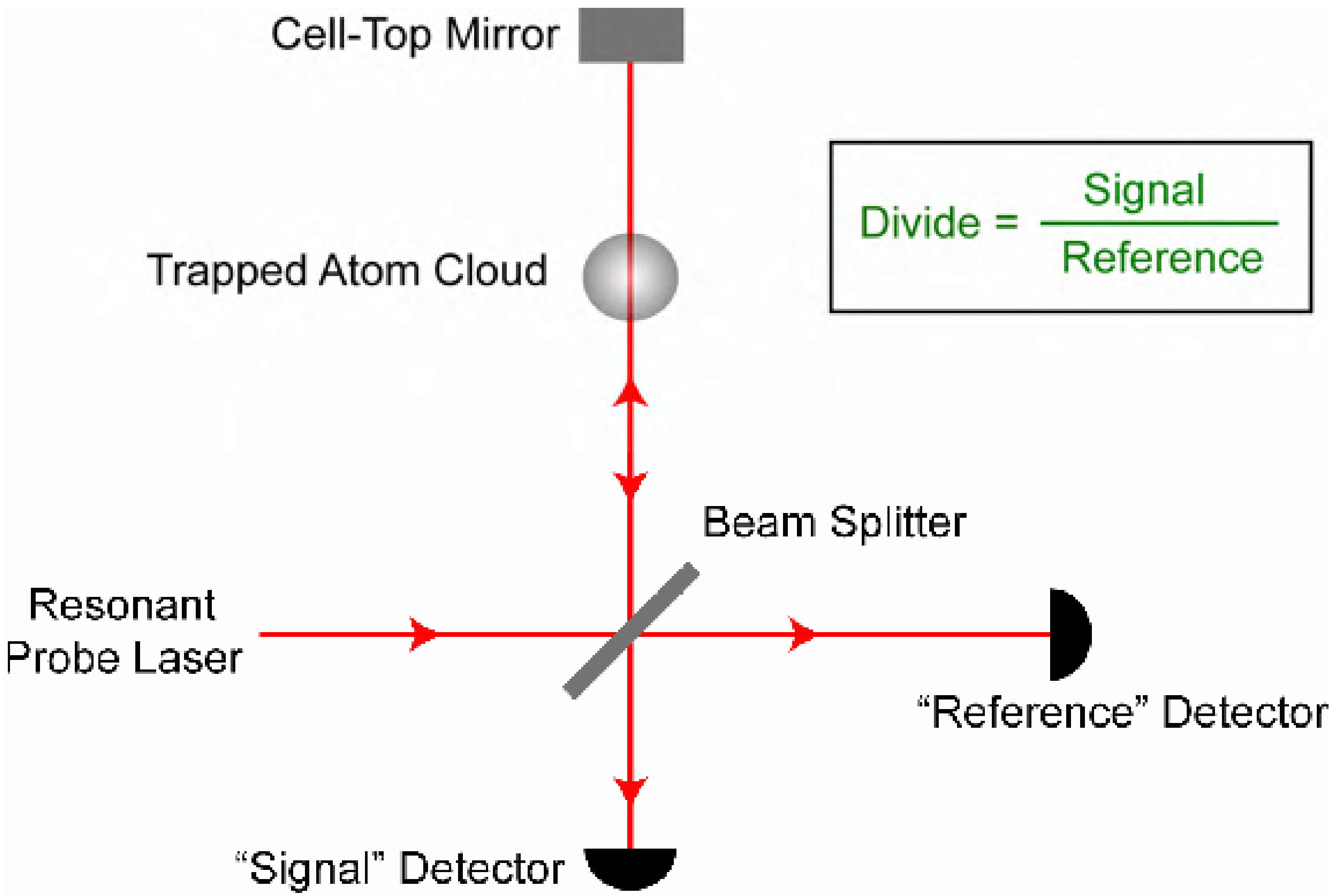
Heat links

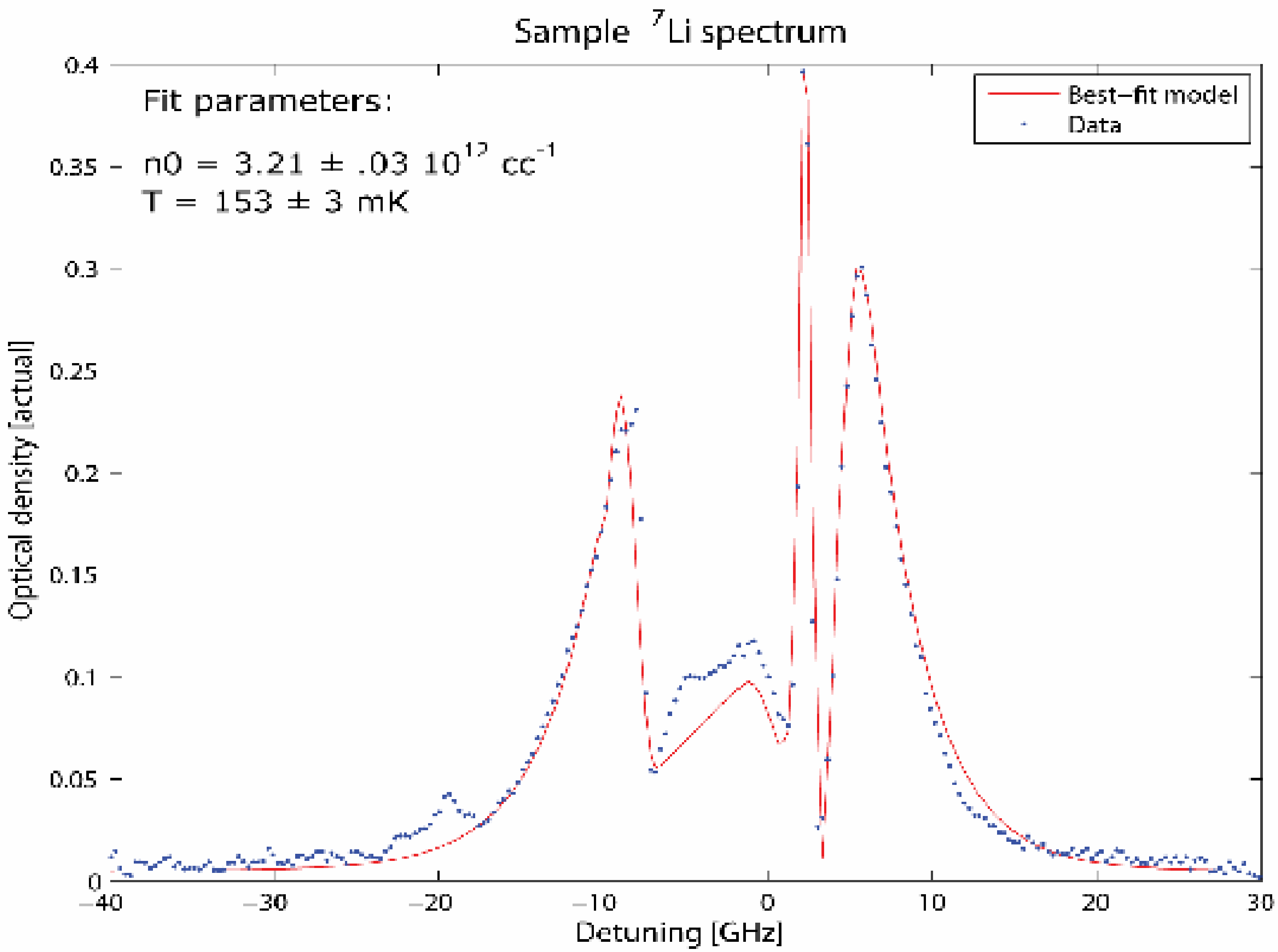
Valve chamber

Experimental cell with pump out and trapping regions



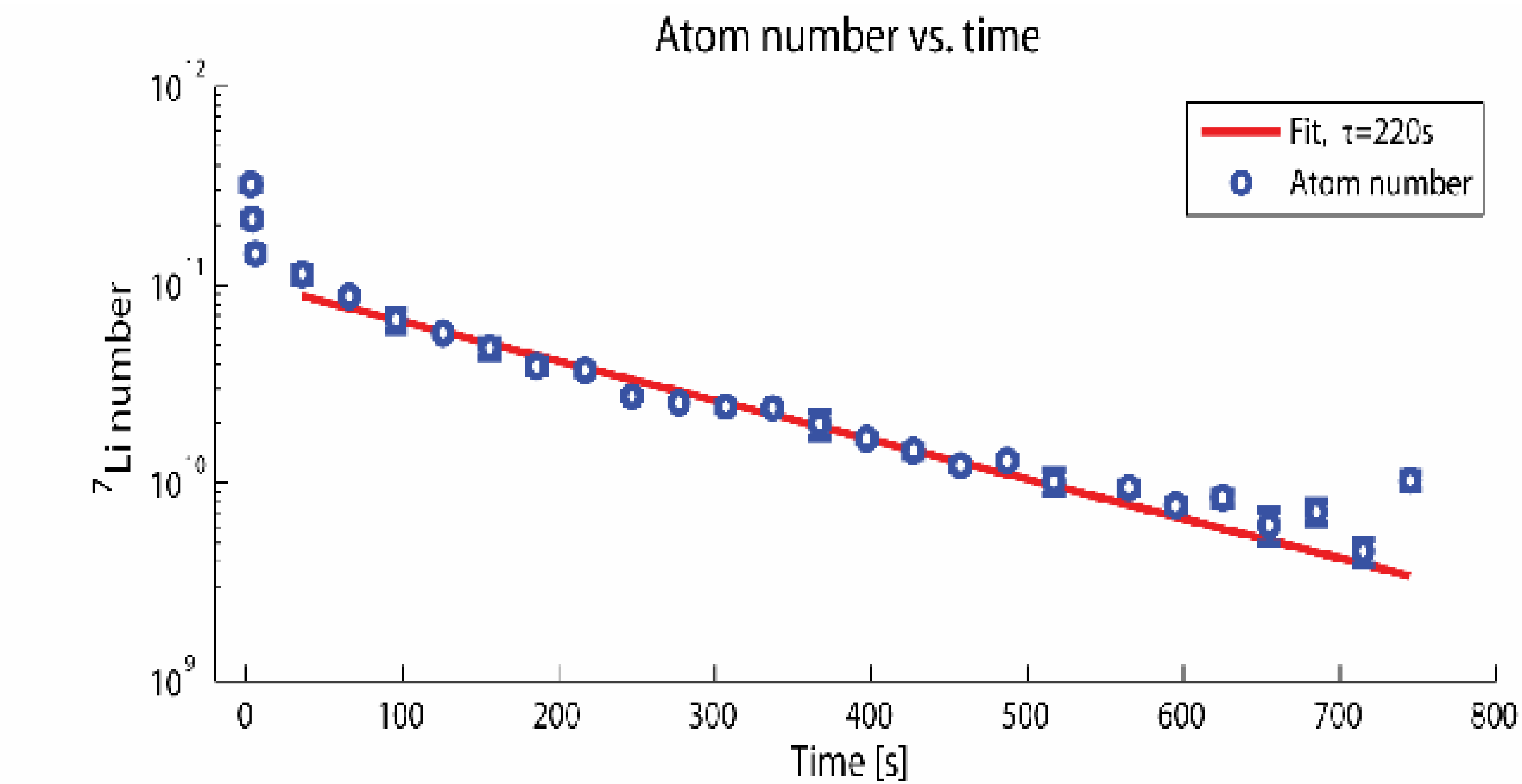
Absorption Spectroscopy





Sample ^{7}Li spectrum
Fit parameters:
n0 = 3.21 ± .03 10^{12} cc^{-1}
T = 153 ± 3 mK
Best−fit model
Data
Optical density [actual]
Detuning [GHz]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
−40
−30
−20
−10
0
10
20
30

Li Trapping: $1\mu_B$ S-state atom



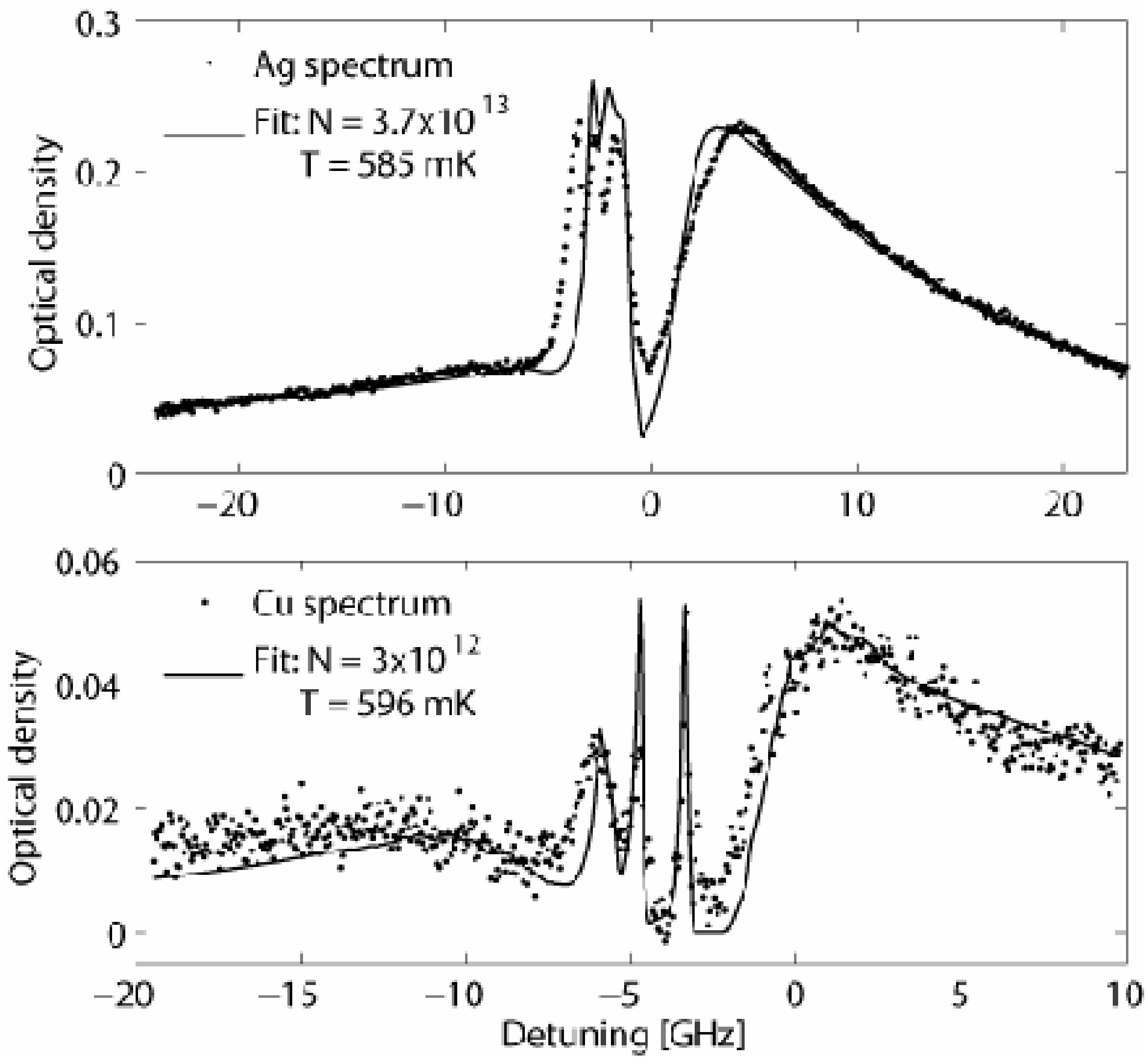
Demonstrated first buffer gas cooling and trapping of 1 μ_B atoms!

The Noble Metals

	Cu	Ag	Au
Ground state config.	$3d^{10}4s$	$4d^{10}5s$	$4f^{14}5d^{10}6s$
Z	29	47	79
λ(nm)	327	327	243

- All are hydrogen like $^2S_{1/2}$ ground states.
- Atomic masses are more favorable than Li for trapping.

Trapped Ag, Cu



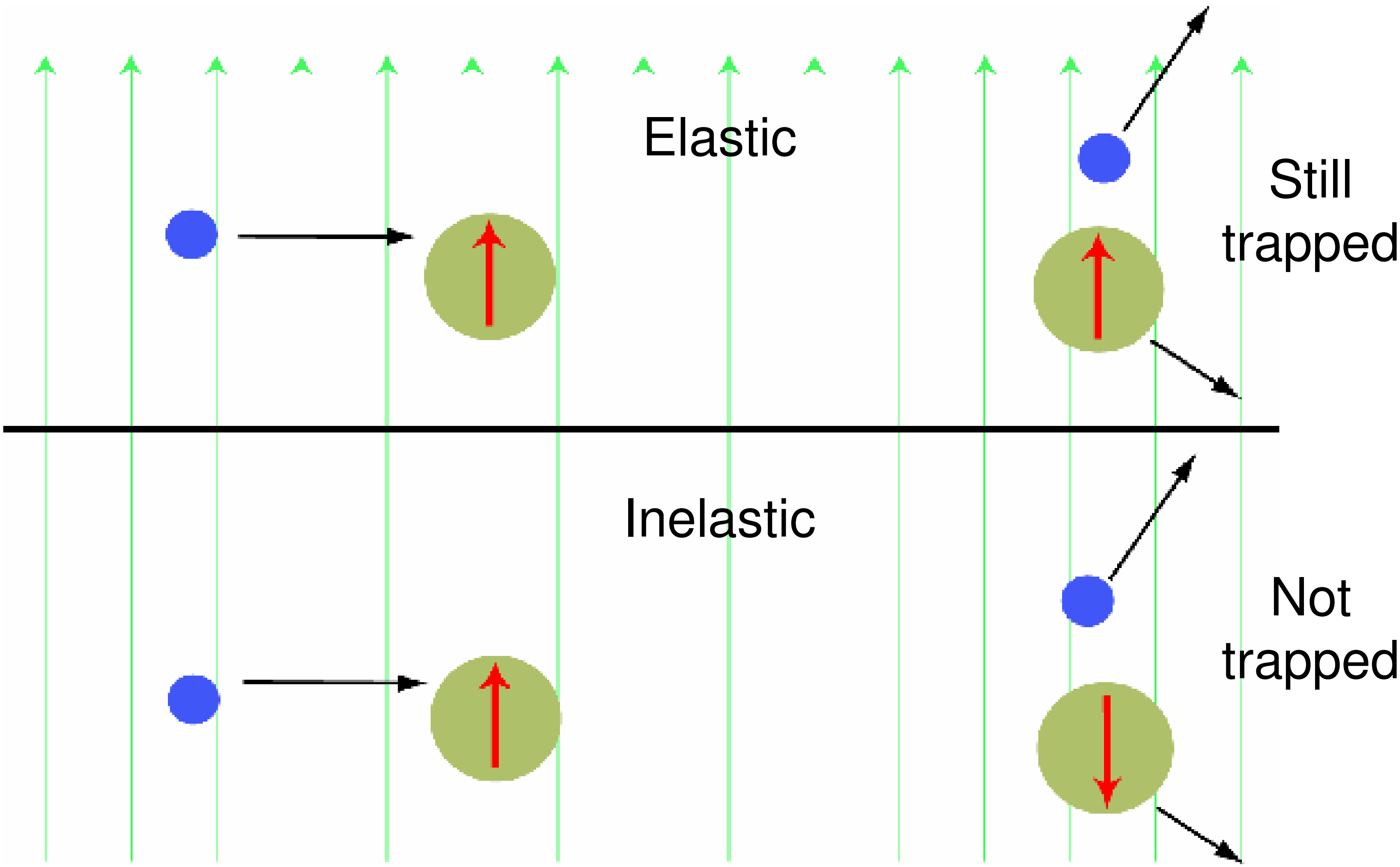
Probe $^2S_{1/2} \rightarrow {}^2P_{3/2}$ (328 nm)

Ag 1/e lifetime ~ 2.5 s

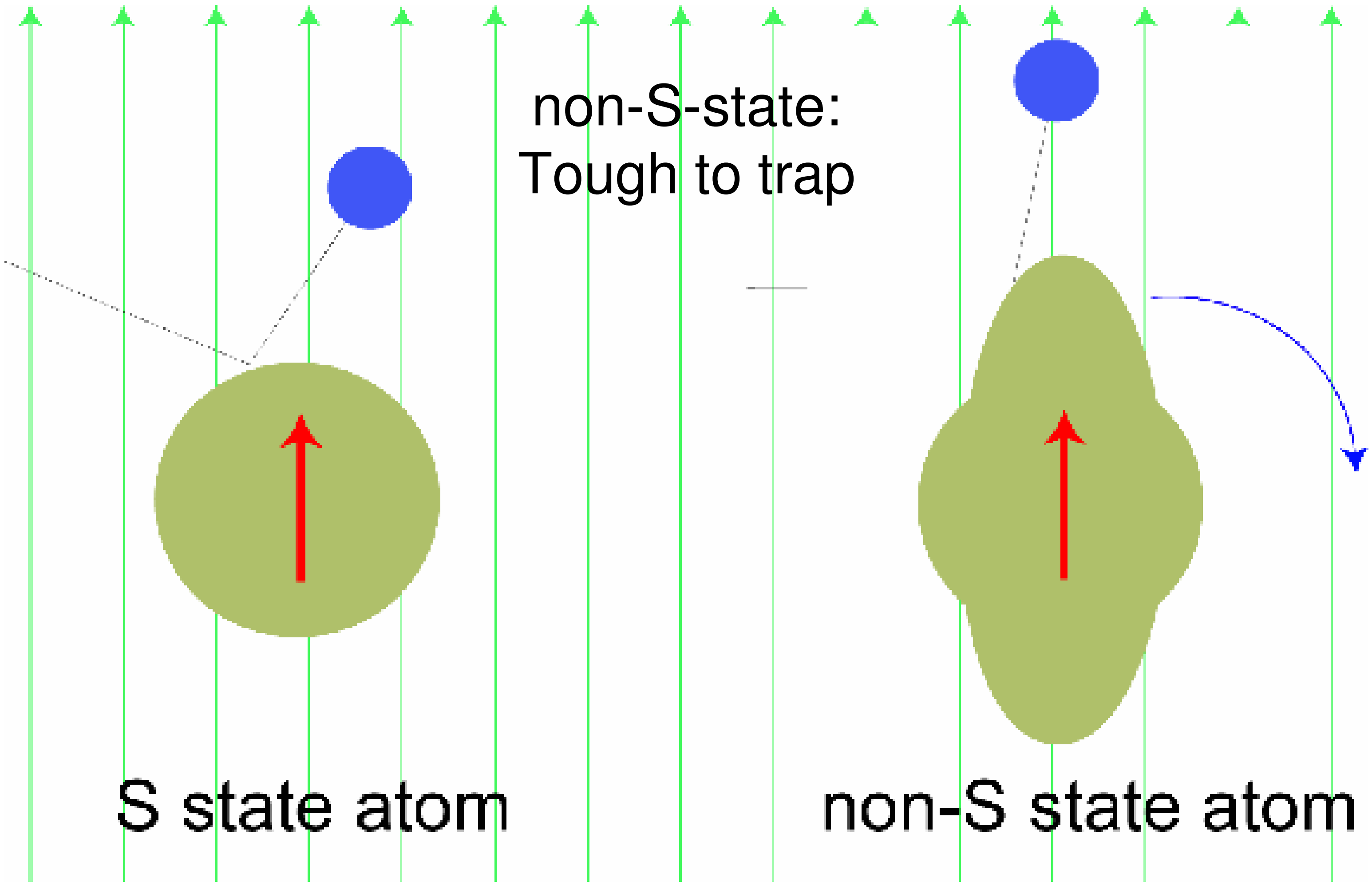
Probe $^2S_{1/2} \rightarrow {}^2P_{3/2}$ (325 nm)

Cu 1/e lifetime ~ 5 s

Elastic vs. Inelastic Collisions



S-state vs. non-S-state



Elastic to Inelastic Ratio

Inelastic = trap loss

Elastic = thermalization

$$\tau_d = \frac{1}{n\sigma_{el} v_{th}}$$

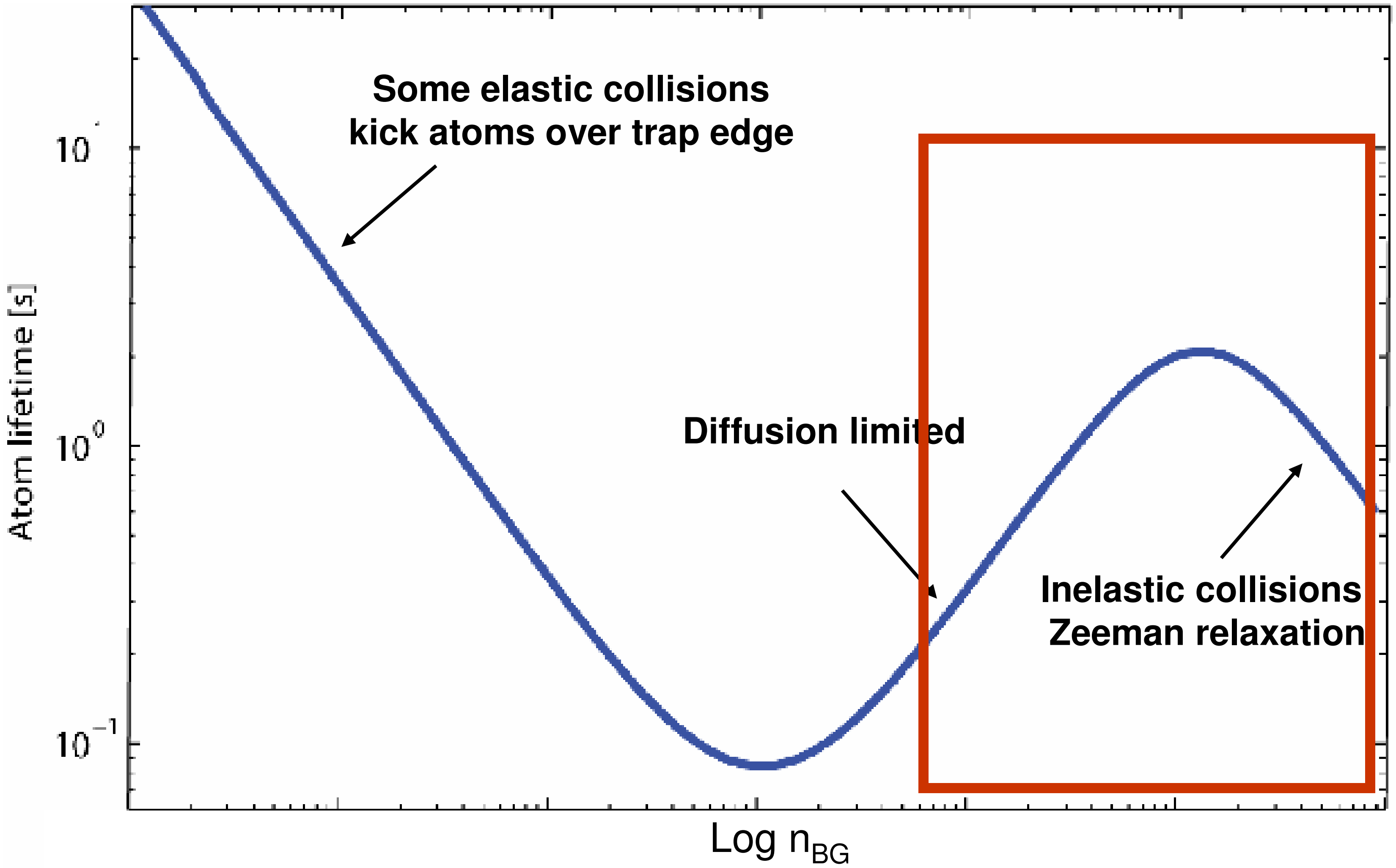
$$\boxed{\gamma = \frac{\sigma_{el}}{\sigma_{in}}}$$

$\gamma > 10^4$ for possible trapping

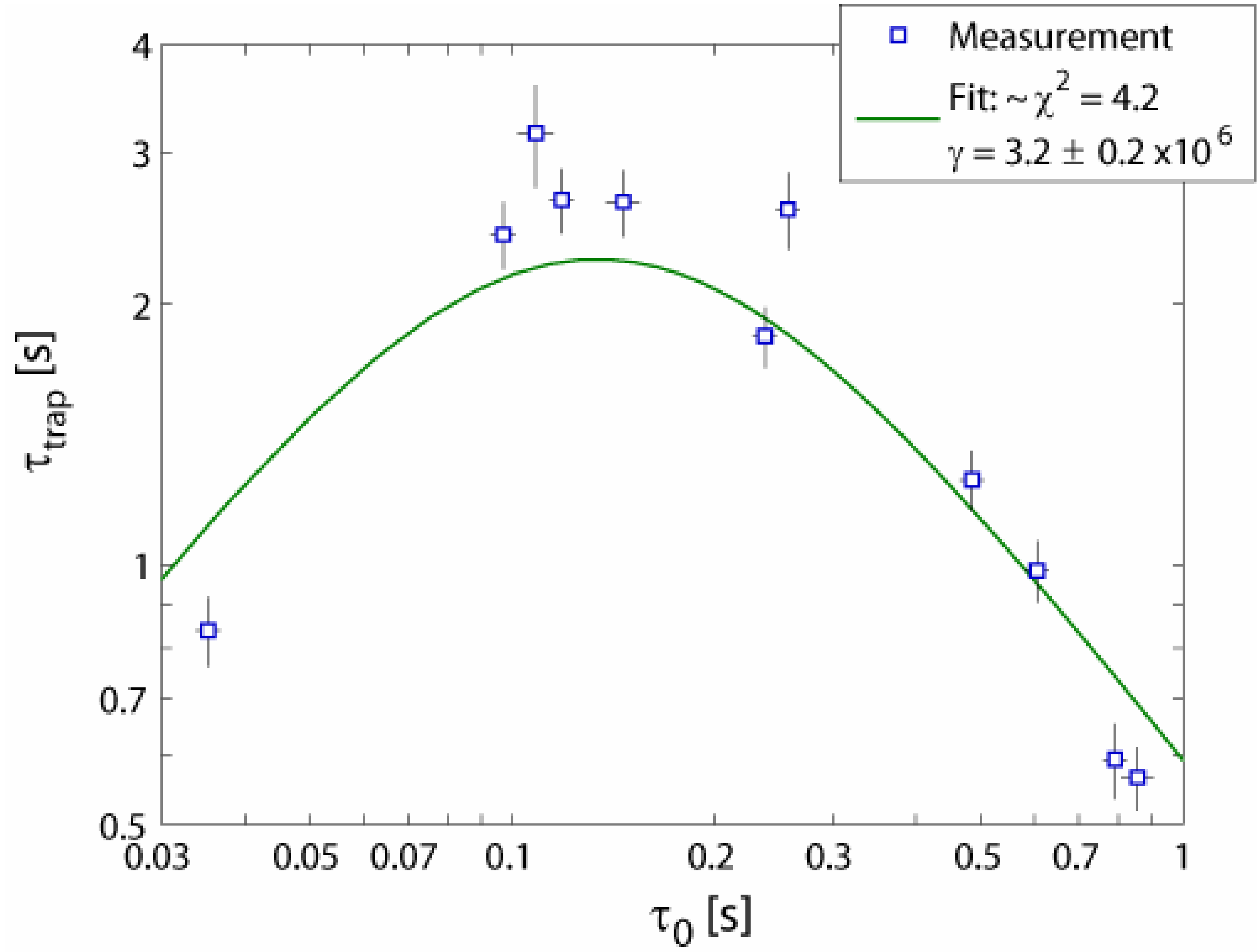
Ratio is an indicator of anisotropy.

Or how S-like a many-electron atom is!

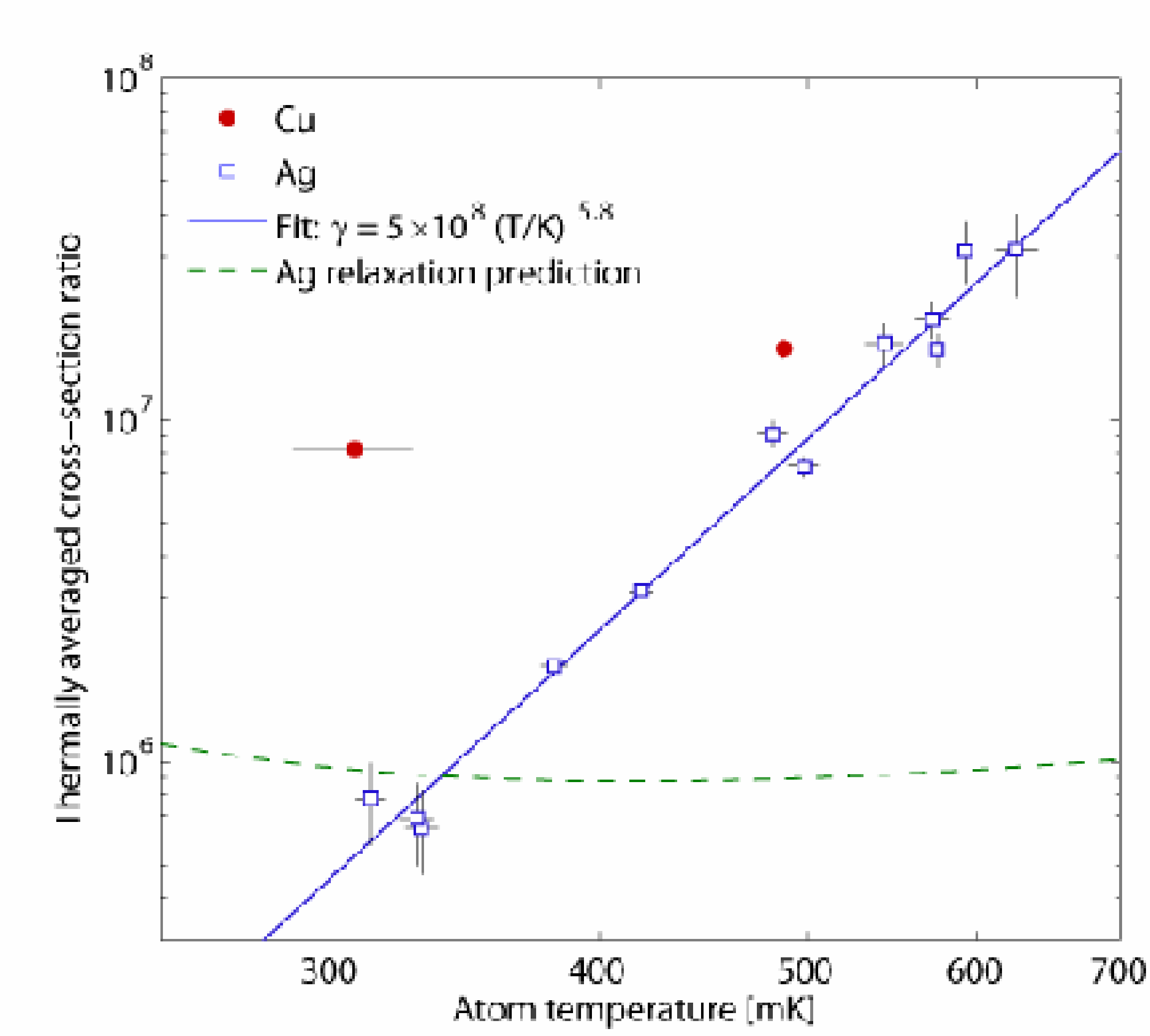
BG Effects on Trap Lifetime



Ag Trap Lifetime vs. τ_d



Temperature Dependence



$\gamma_{Ag}, \gamma_{Cu} > 10^6$

S-state behavior confirmed

$\gamma_{Ag} \sim T^6$

Not expected

Brahms, N., et. al. -- submitted.

Conclusion

Successfully trapped $1\mu_B$ Li, Cu, Ag using buffer gas cooling

1. Lithium
   - $>10^{12}$ atoms trapped at T ~ 150 mK
   - Lifetimes ~ 200 seconds
2. Cu, Ag
   - $>10^{12}$ atoms trapped at T < 500 mK
   - Lifetimes ~ 5 s
   - Anomalous Ag inelastic collision dependence on temperature

Removal of the Buffer Gas

- Thermal isolation
- Lengthen trap lifetime
- Study intra-atomic collisions
- Evaporative cooling to possible quantum degeneracy

Rare Earths

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

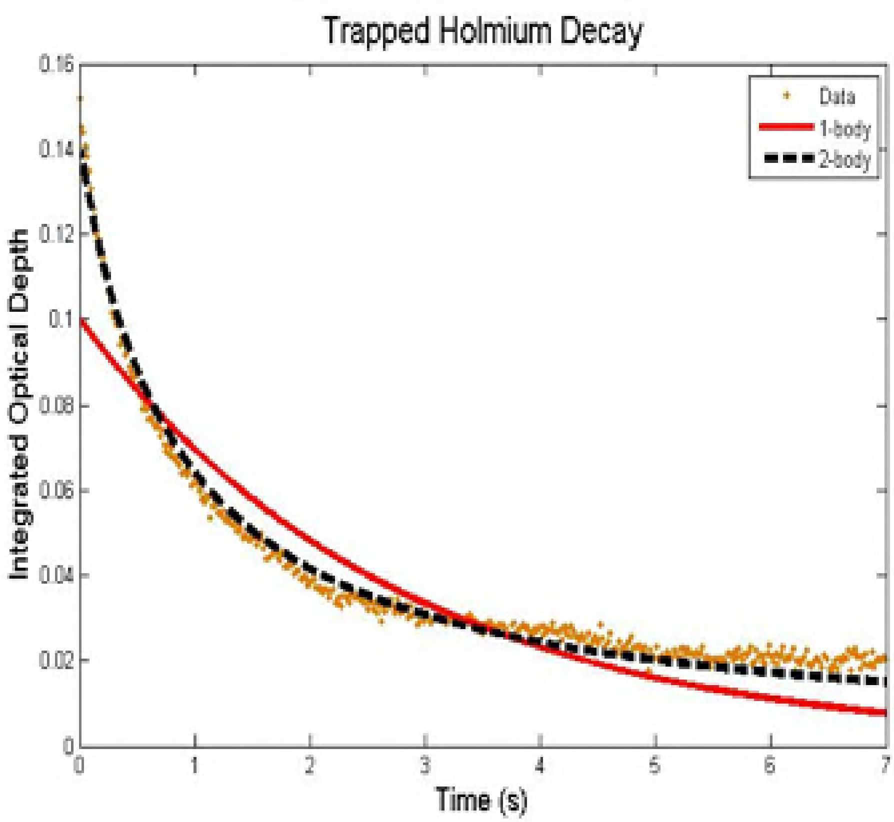
Non S-state -- but repressed anisotropy[1]

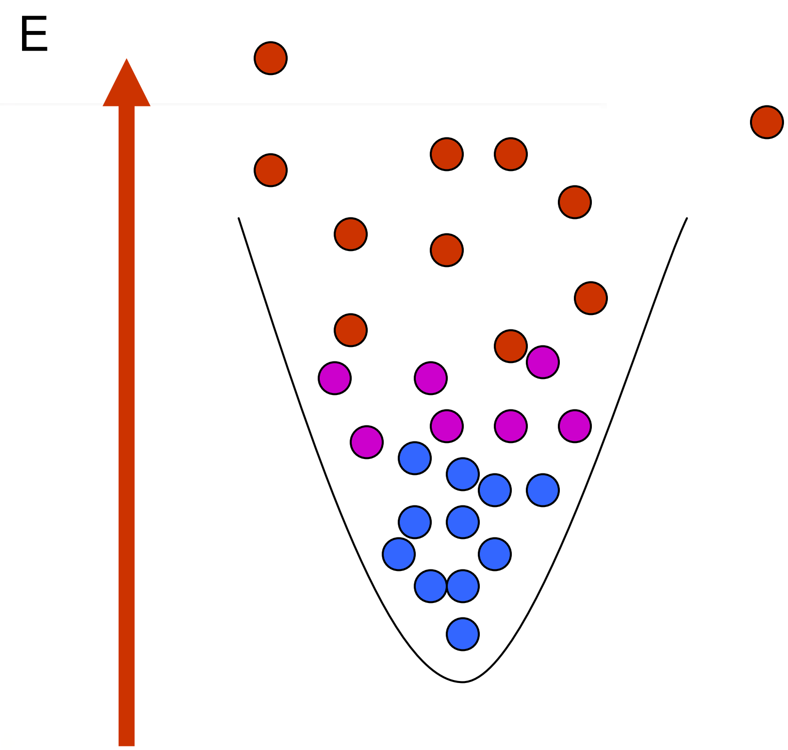
High magnetic moments

[1]Hancox, C., et. al. *Nature,* **431**, 281 (2004).

Future Experiments

Intra-species collisions

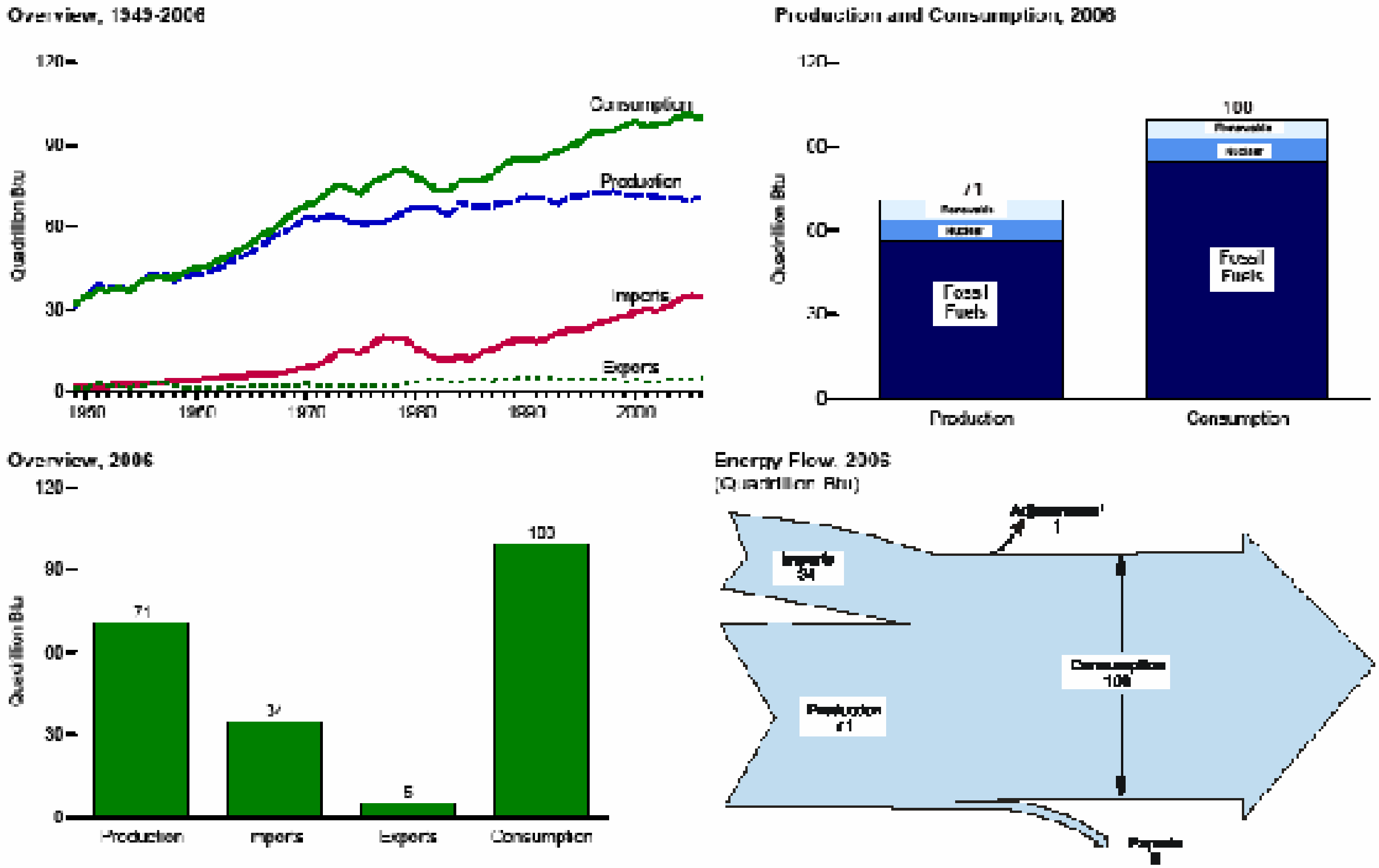




Evaporative cooling

Why am I here today?

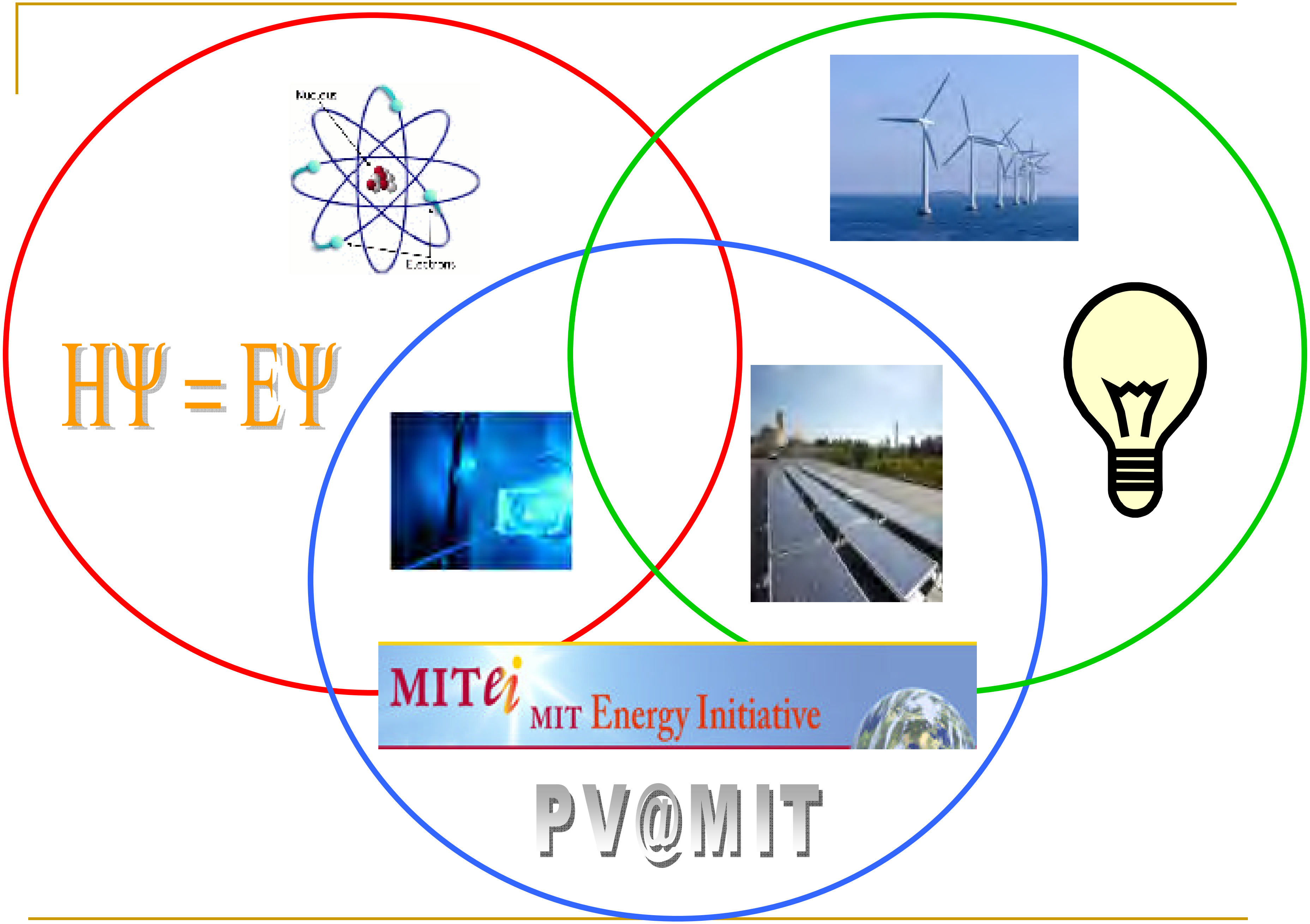
Figure 1.1 Energy Overview



[1] Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for supply.

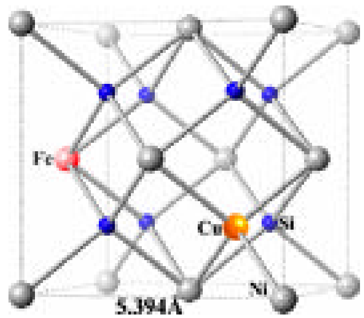
Source: Table 1.1.

4 Energy Information Administration / Annual Energy Review 2006


Nucleus
Electrons
HΨ = EΨ
MITei
MIT Energy Initiative
PV@MIT

PV @ MIT – Buonassisi Lab

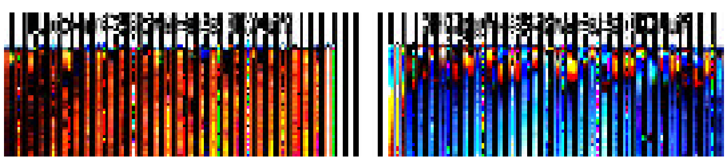
All things PV!



Near Term

Crystalline silicon

- **Increase efficiency**
  - **Defect engineering**
  - **Device architecture**
- **Processing and manufacturing**



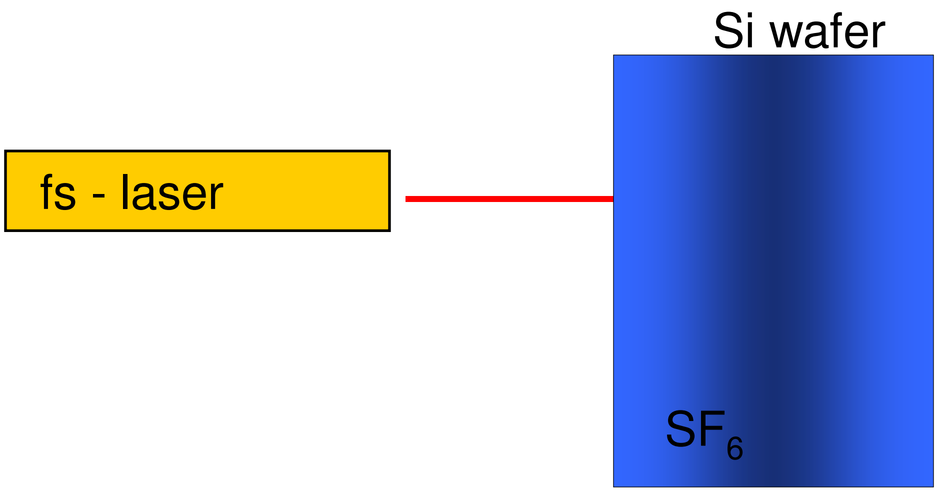
Images courtesy of Tonio Buonassisi.

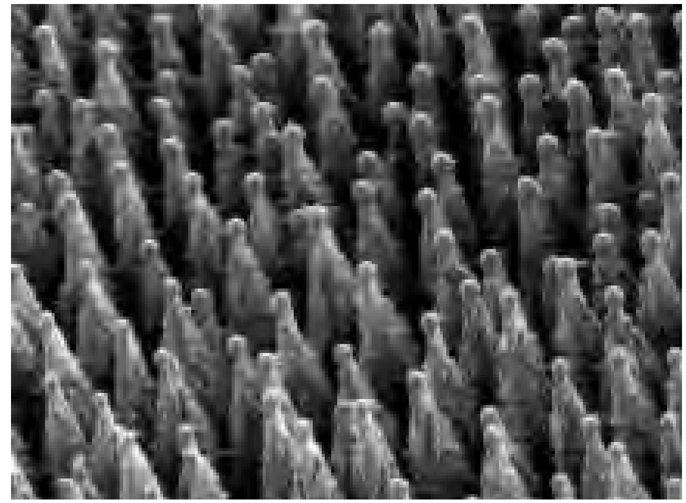
Intermediate Term

Thin Films
- Novel materials
- Abundant

Thin Silicon Project

Femtosecond structured silicon

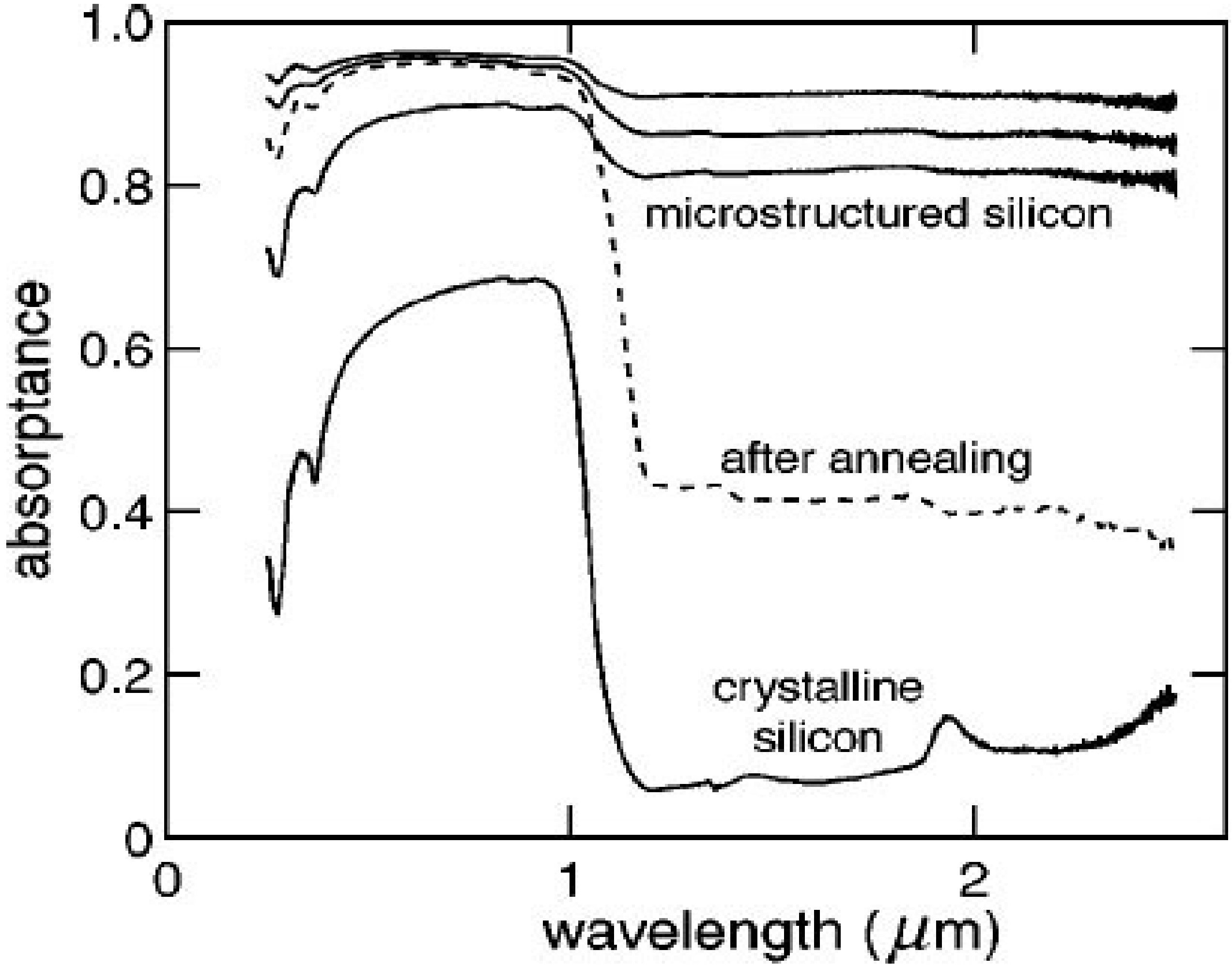




Silicon turned black!

C. H. Crouch, et. al. J. App. Phys. A, 79, 1635-1641 (2004).

Thin (Black) Silicon



Use tools from defect engineering to figure out why this is happening!

Can we use if for PV devices??

More Information

For more information about photovoltaic and energy research at MIT

http://pv.mit.edu

http://web.mit.edu/mitei